

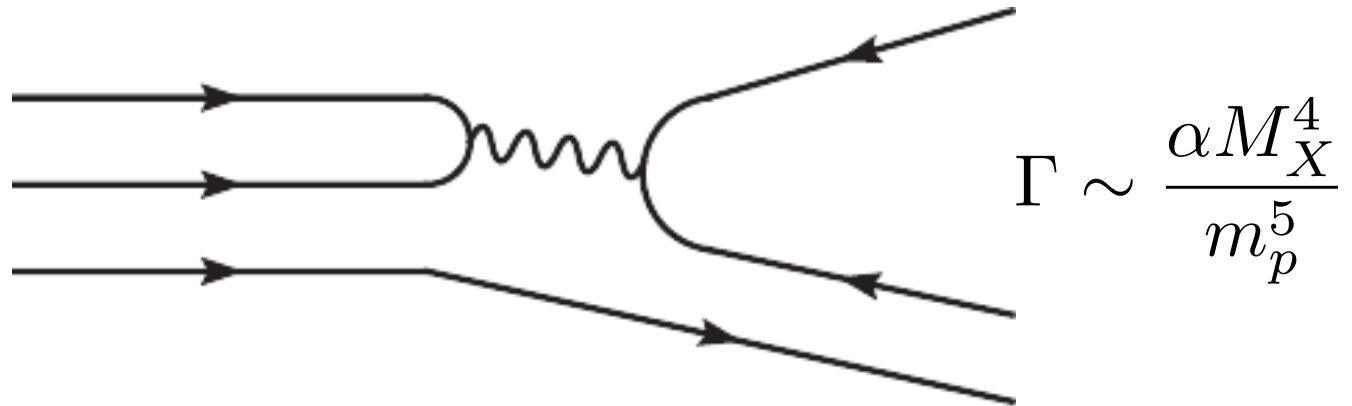
# Proton Decay with Liquid Argon and Water Cherenkov Detectors

Ed Kearns — Boston University  
October 16, 2008

With much reference to:  
A. Bueno et al. hep-ph/0701101

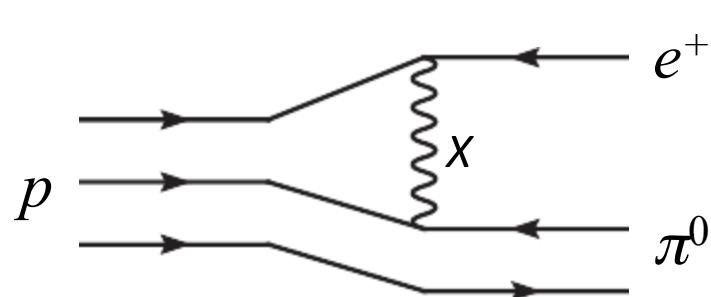
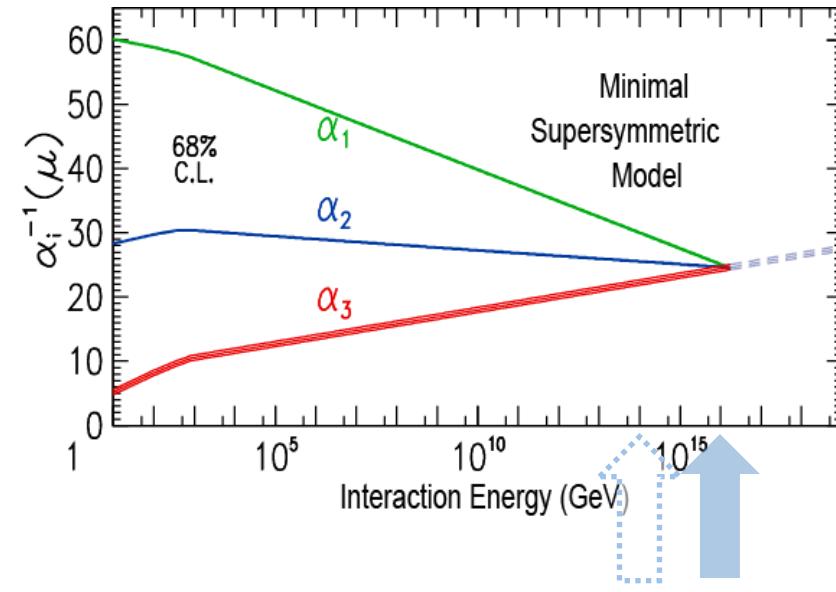
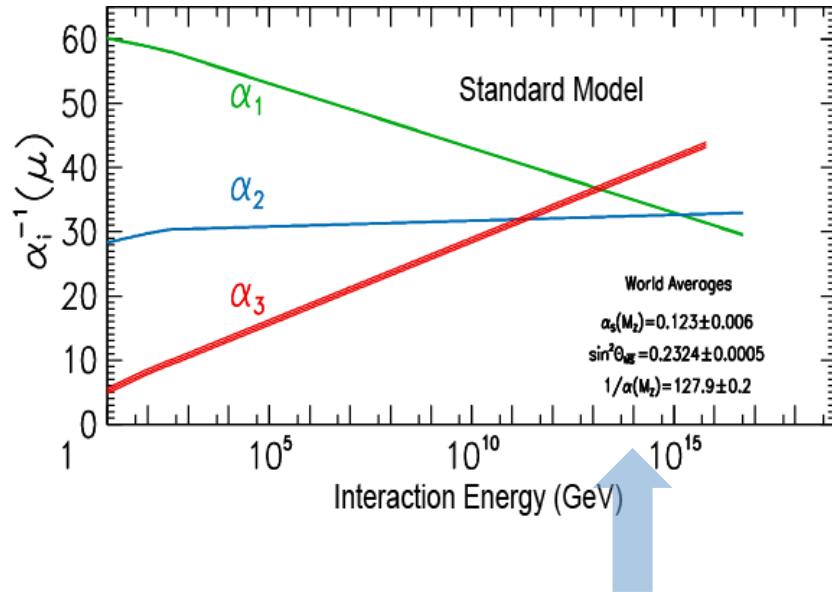


# Proton Decay

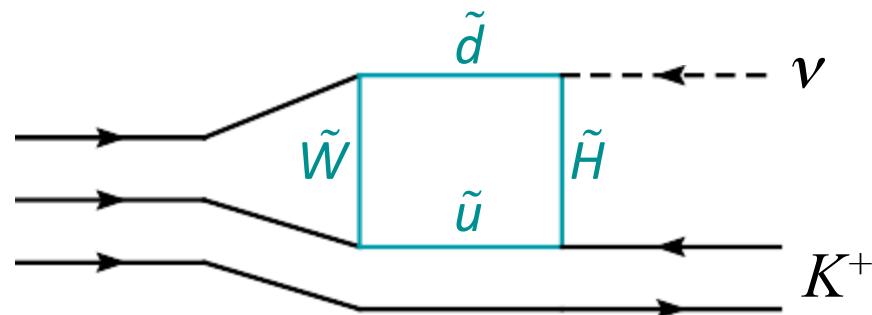


- ★ Highly prized physics motivation:  
Grand Unification of strong, weak, and electromagnetic forces!  
New force carrying particle!
- ★ Connections to neutrino mass, cosmology, inflation, BAU ...
- ★ Test of basic symmetries: baryon number and lepton number.
- ★ Supersymmetric versions of GUTs are of great interest and value.
- ★  $\sim 10^{15}$  GeV energy scale – inaccessible to accelerators.
- ★ Long lifetime (from SK) is already a difficult constraint  
which new models must work hard to evade. The limits are interesting!

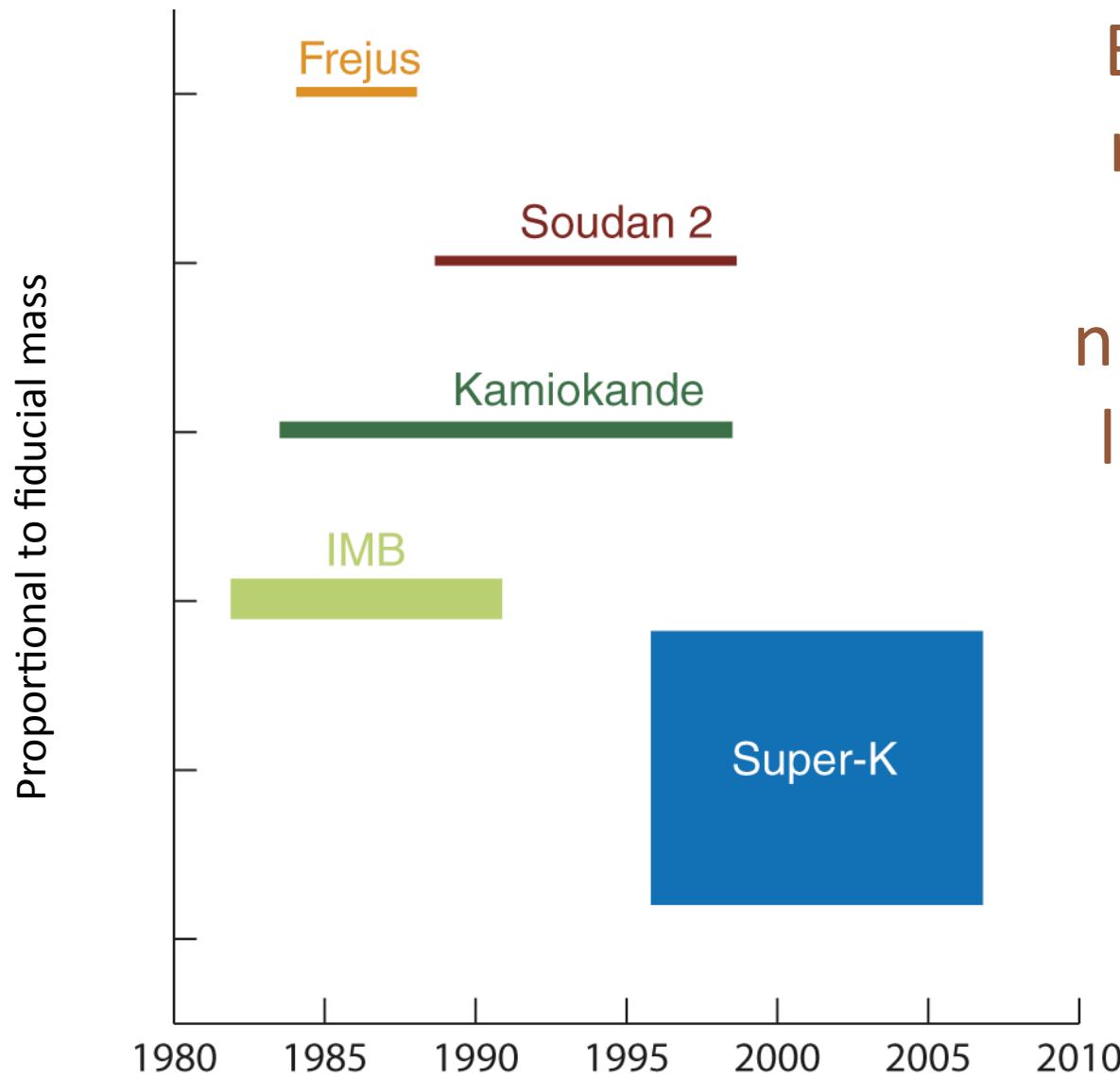
# Unification of Running Coupling Constants



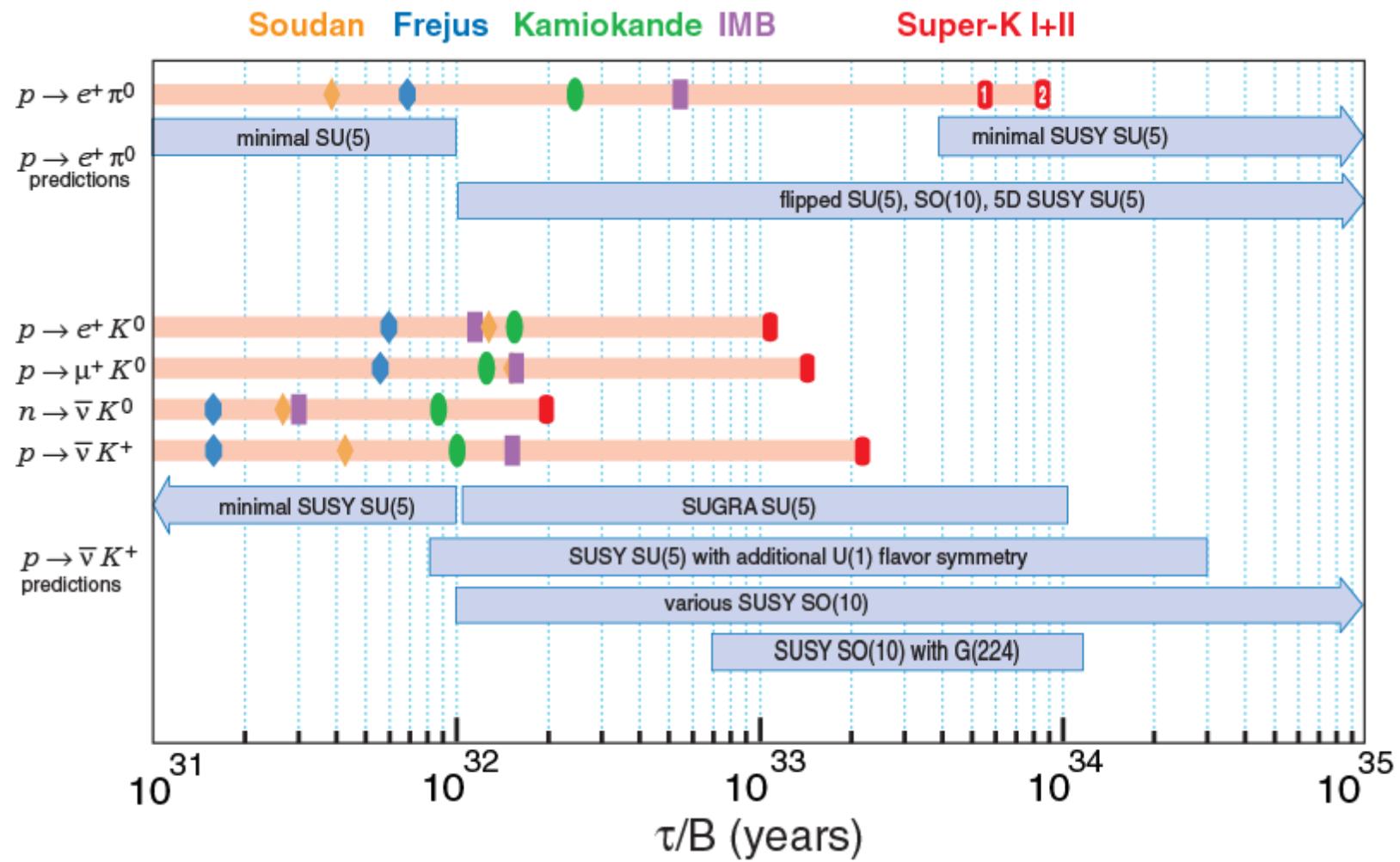
$\tau/B = 4.5 \times 10^{29 \pm 1.7} \text{ years}$  SU(5)  
 $\tau/B > 8.4 \times 10^{33} \text{ years}$  SK I + II



$\tau/B = 10^{29-35} \text{ years}$  SUSY  
 $\tau/B > 2.3 \times 10^{32} \text{ years}$  SK I

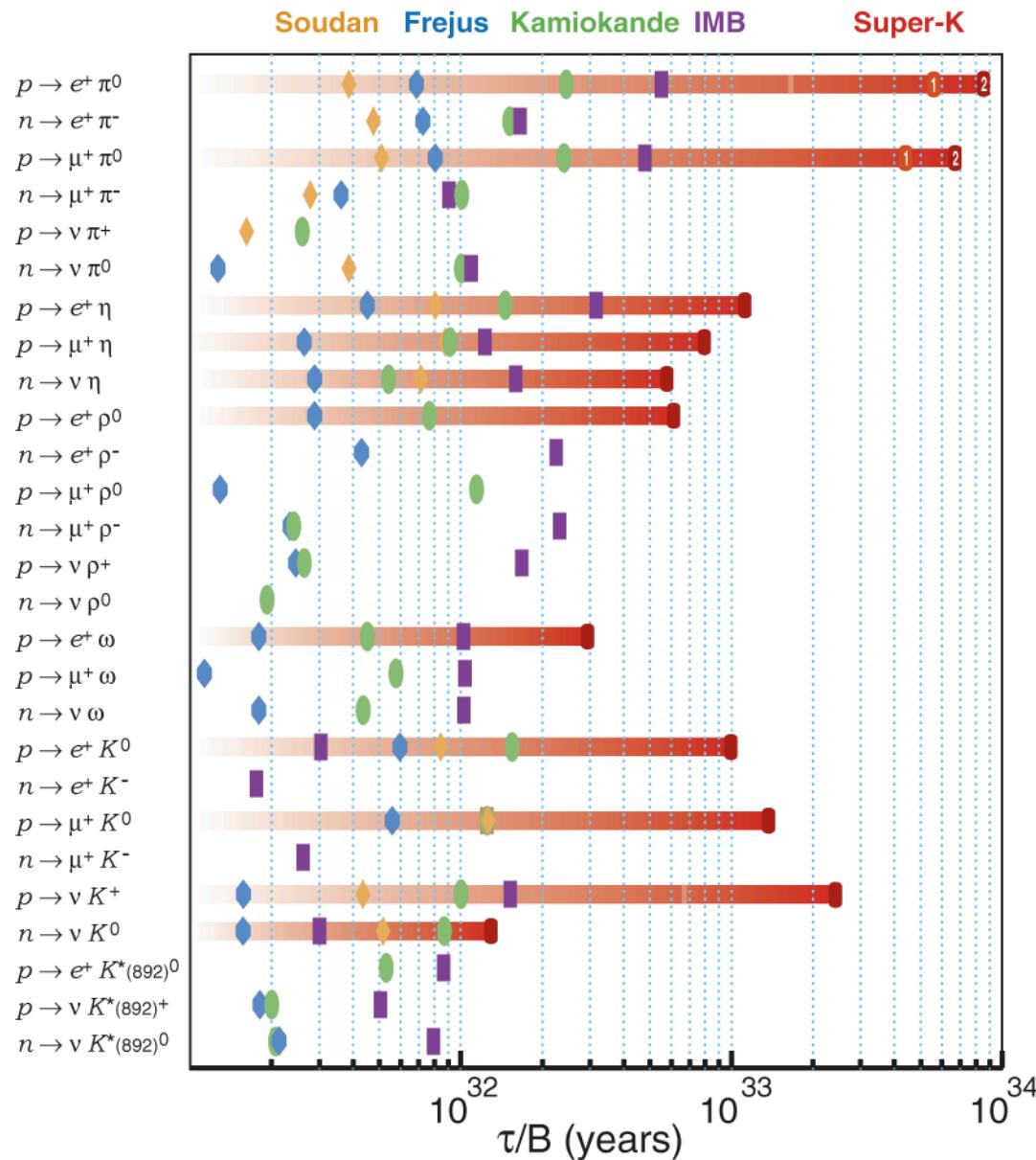


Experiments  
represented  
with best  
nucleon decay  
limits in PDG



Objective is to improve by at least 1 order of magnitude.  
 Desirable to probe both  $e^+\pi^0$  and  $K^+\bar{v}$  (plus many many other modes)

# Antilepton plus meson modes



Conserves B-L

IMB has most in PDG  
(for now)

Super-K has only  
searched for favored  
channels (for now)

There are good reasons  
to cover many of these  
modes...

# Beyond Anti-lepton plus meson modes

$$p \rightarrow \mu^- \pi^+ K^+$$

$B + L$

$$n \rightarrow \bar{n}$$

$\Delta B = 2$ , TeV < scale < GUT

$$pp \rightarrow K^+ K^+$$

$\lambda''_{uds} < 10^{-8}$

$$p \rightarrow e^- \pi^+ \pi^+ \nu \nu$$

6D

$$n \rightarrow \nu \nu \nu$$

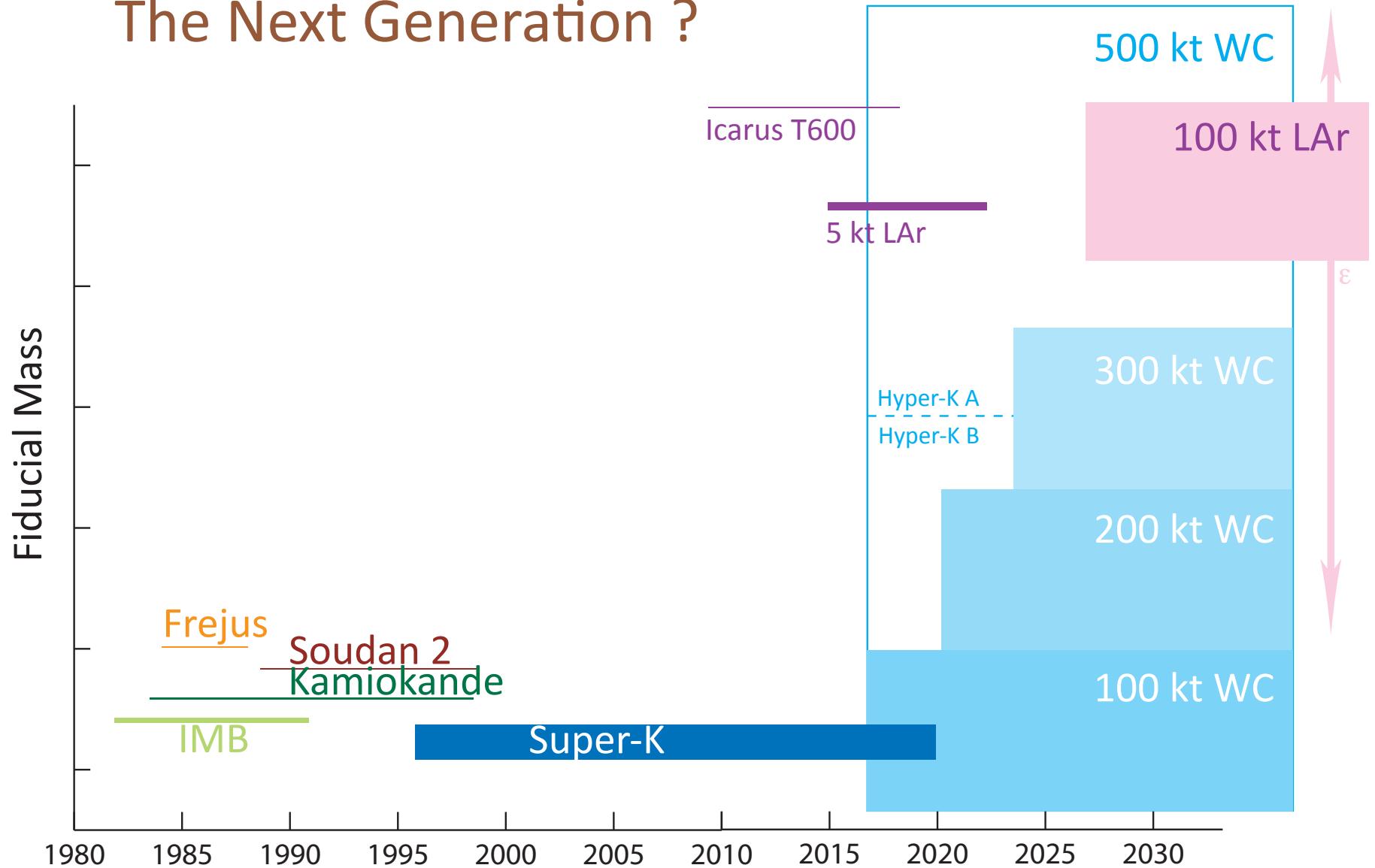
invisible

$$p \rightarrow e^+ \gamma$$

radiative

Many topics...

# The Next Generation ?



## Water Cherenkov

### The GOOD:

Cheap mass  
Energetic EM showers, muons;  $\mu$  decay  
Mature, time-tested technique  
 $e^+ \pi^0$

### NOT SO good:

Sub-threshold charged particles  
Mature technique is boring

### Questions for the next generation:

PMT coverage (40% - 20% - 5%)?  
Can we reduce per channel cost?  
Details, details, details...

## Liquid Argon

### The GOOD:

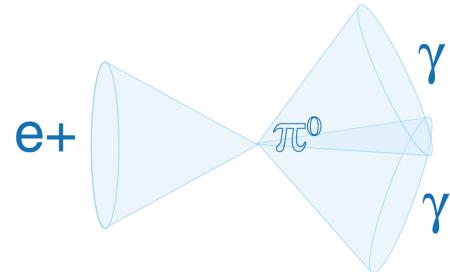
High resolution and detail  
Charged Particle dE/dx  
Exciting “new” technology  
 $K^+ \nu$

### NOT SO good:

Unknowns: cost, feasibility, operation, safety

### Questions:

Design paths (wires, GEMs, vacuum etc.)  
When will we see a detector operate for a year?  
Is 100 kton realistic?



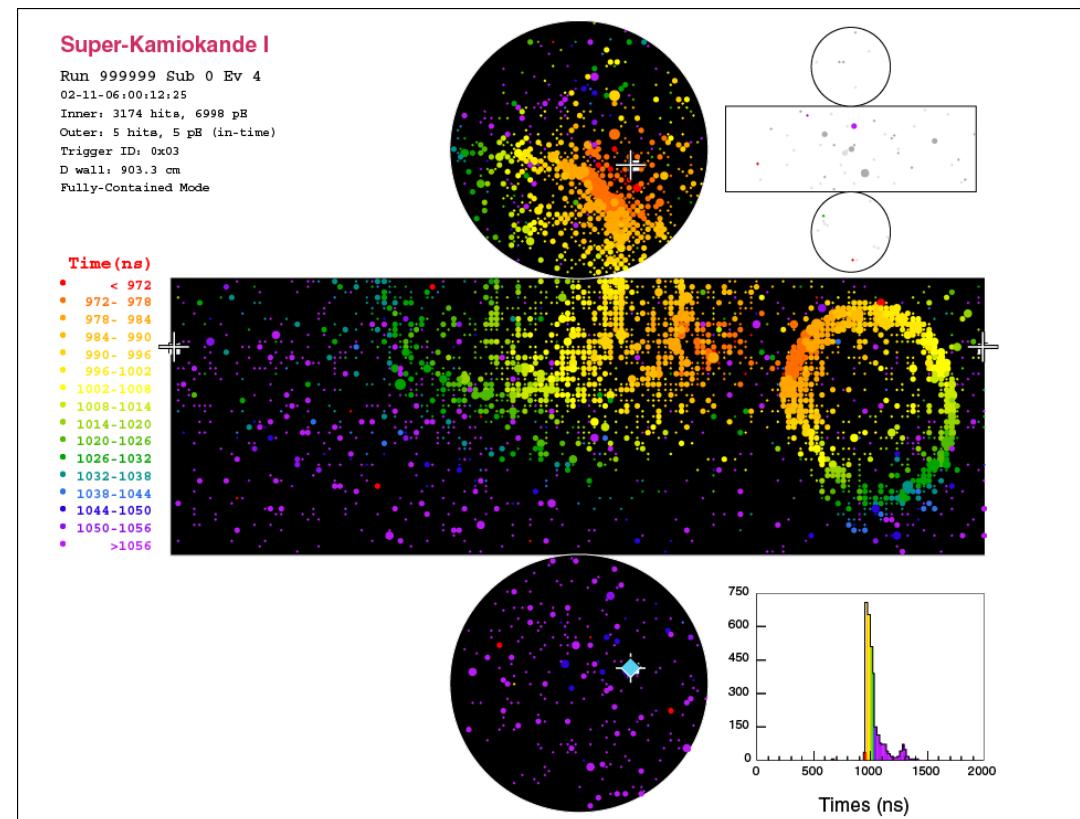
## Event selection criteria:

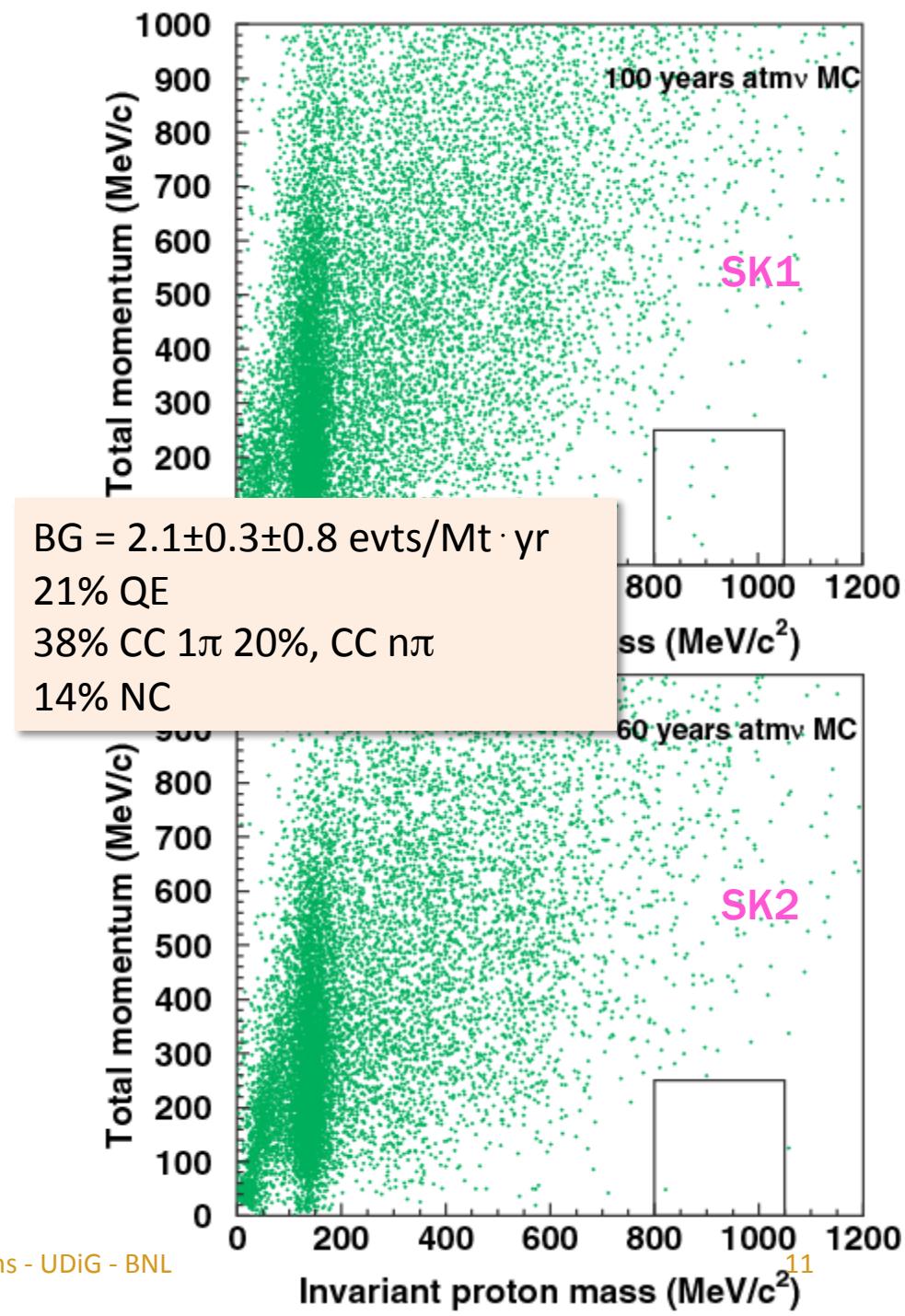
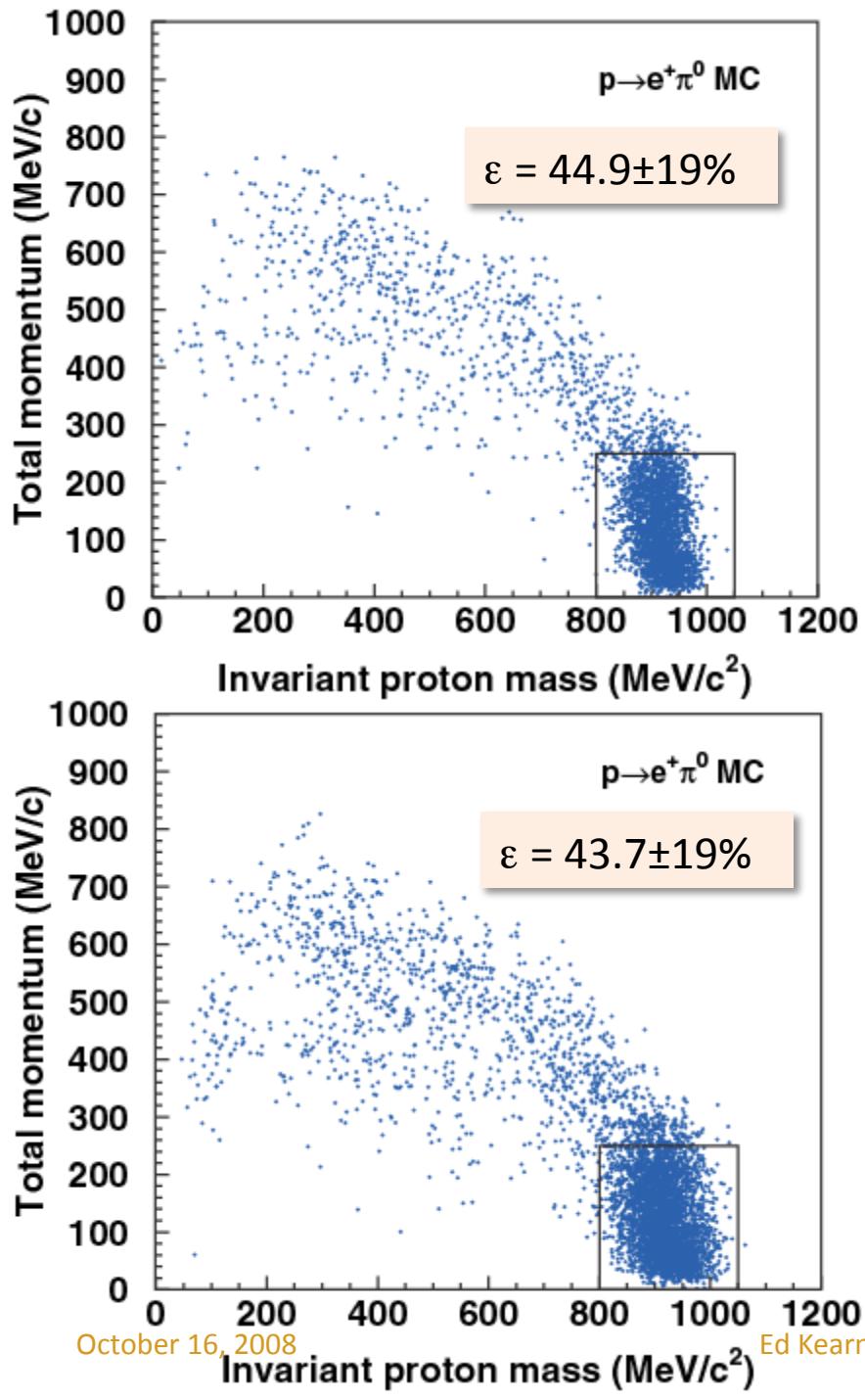
- Fiducial volume
- Fully contained
- 2 or 3 rings
- All rings are e-like
- $\pi^0$  mass 85-185 MeV/ $c^2$
- No  $\mu$ -decay electrons
- Mass range 800-1050 MeV/ $c^2$
- Net momentum < 250 MeV/ $c$

For  $\mu^+ \pi^0$ :

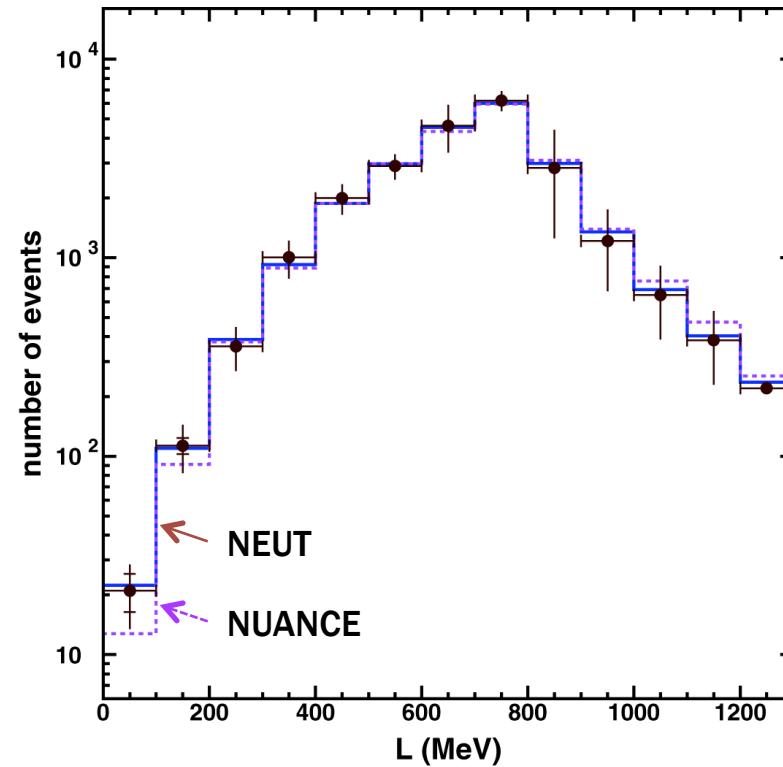
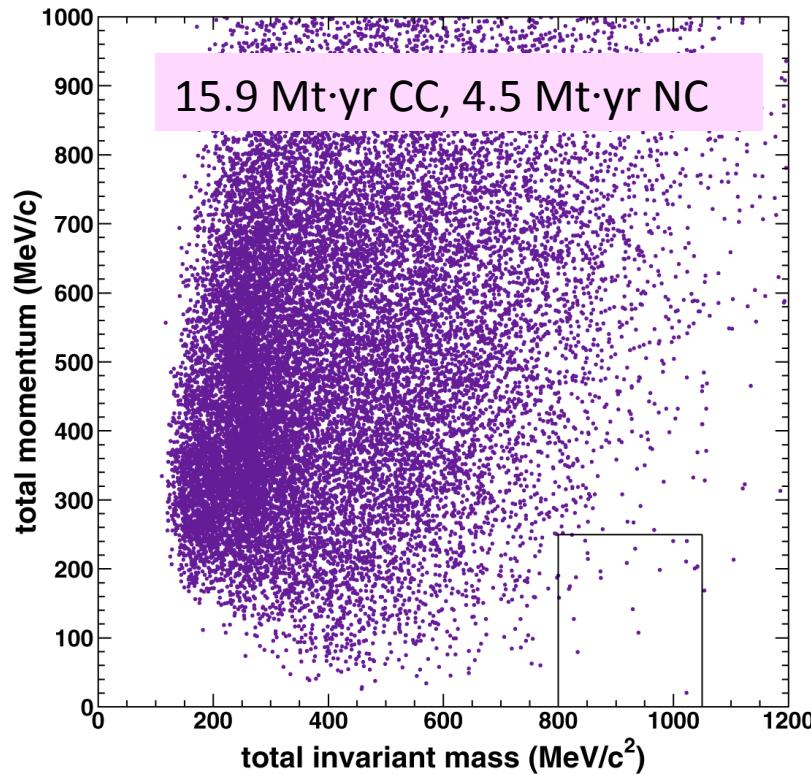
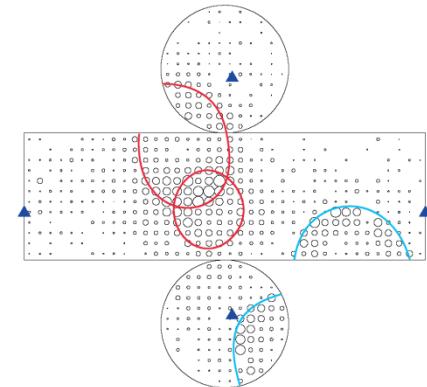
- 1  $\mu$ -like ring  
of correct momentum
- 1 decay electron

Example event: ( $p \rightarrow \mu^+ \pi^0$ )

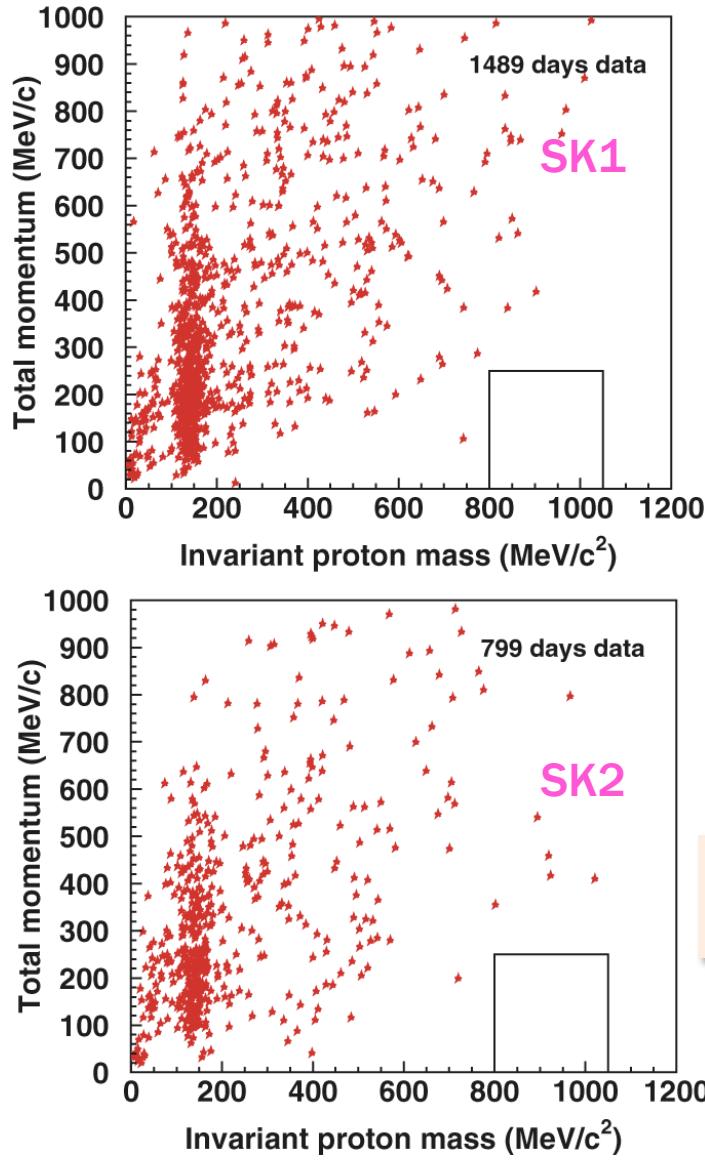




# Direct measurement of proton decay background using K2K beam (1KT near detector)



$$e^+ \pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33} (\text{stat})^{+0.45}_{-0.51} (\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$



## $p \rightarrow e^+ \pi^0$ Search Results

	SK-I	SK-II
Detection efficiency	$44.9 \pm 19\%$	$43.7 \pm 19\%$
Background estimate	$0.30 \pm 0.04 \pm 0.11$ events	
Exposure	$1489.2$ d ( $91.6$ kt·yr)	$798.6$ d ( $49.1$ kt·yr)
Data	0	0
Lifetime limit (90% CL)	$5.5 \times 10^{33}$ yr	$2.9 \times 10^{33}$ yr

$\tau/\text{BR} > 8.2 \times 10^{33}$  yr (90% CL)

Super-K Preliminary

# $p \rightarrow e^+ \pi^0$ in Liquid Argon

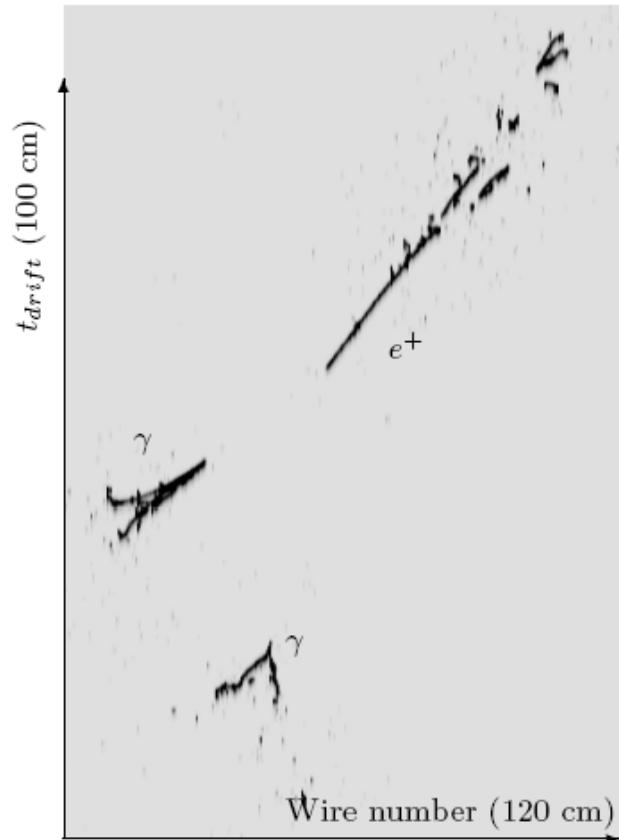


FIG. 14: Simulated  $p \rightarrow e^+ \pi^0$  event. The displayed area covers  $120 \times 100 \text{ cm}^2$ .

$e \approx 45\%$   
 $\text{BG} \approx 1 \text{ evts/Mt} \cdot \text{yr}$

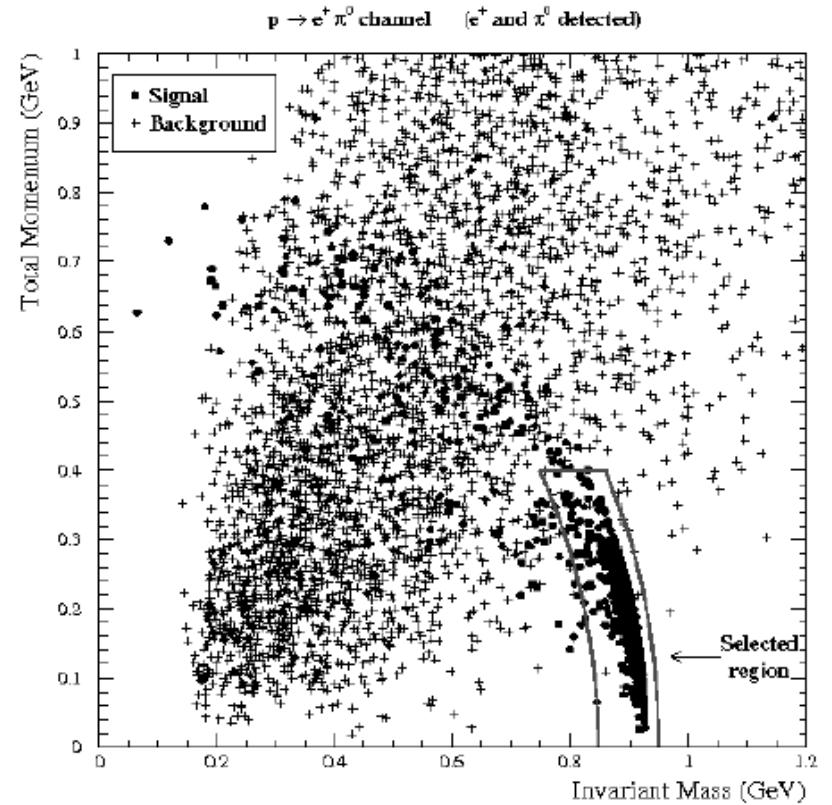
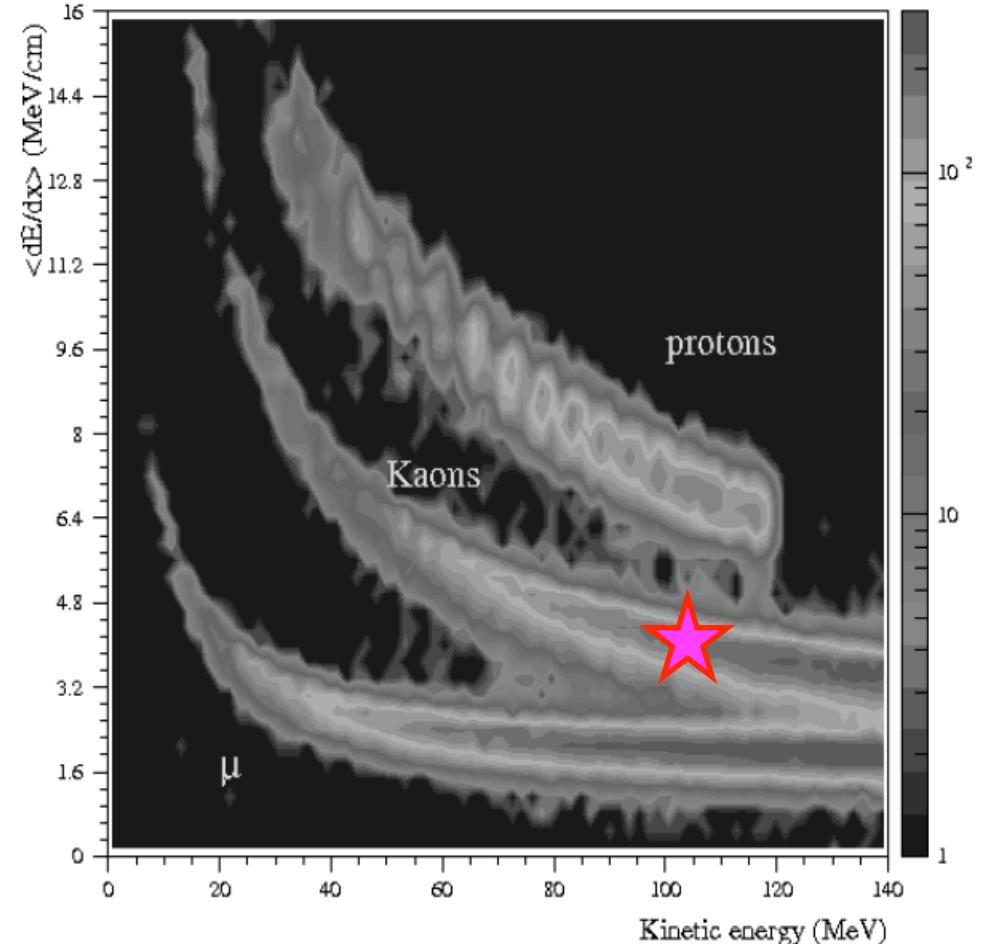
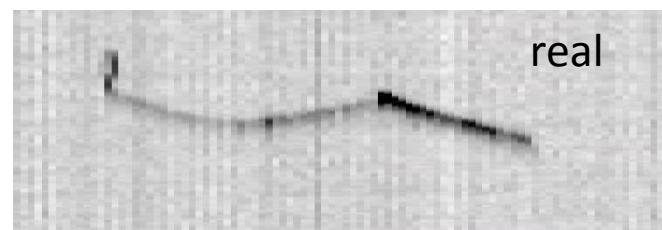
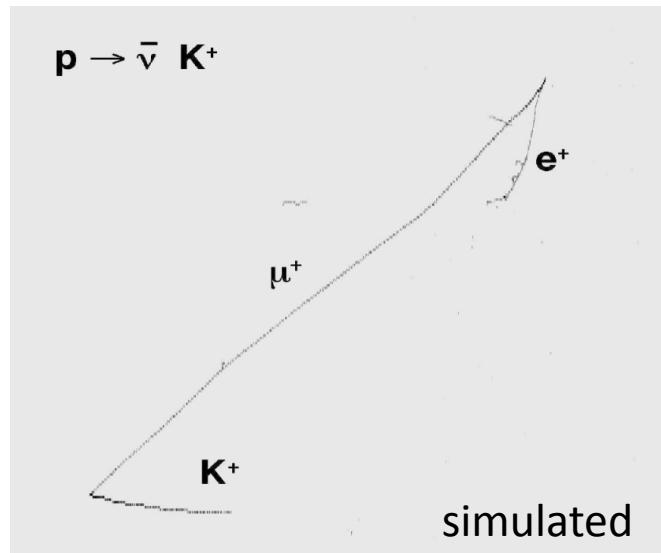


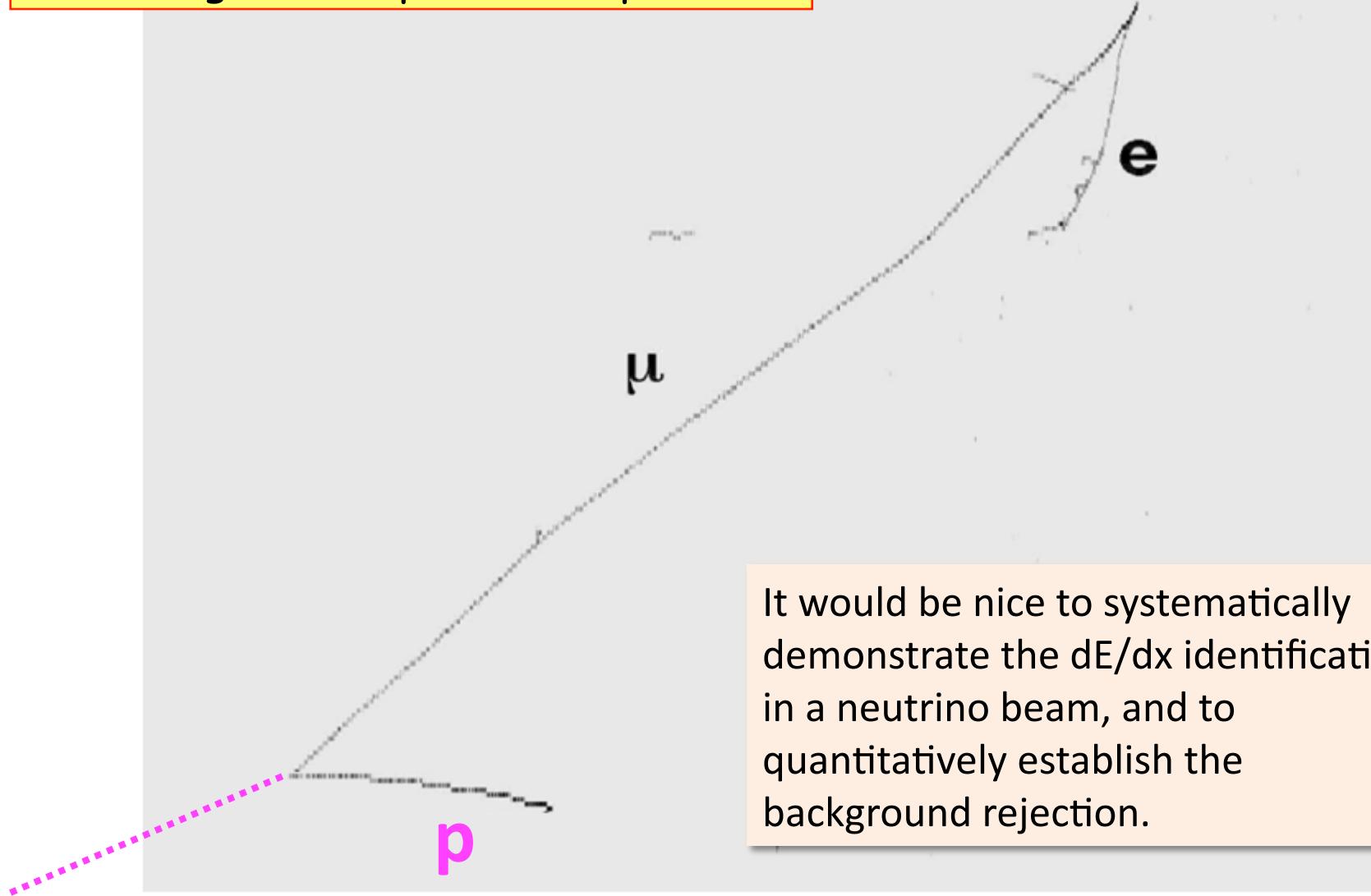
FIG. 16: Kinematic cut in the  $p \rightarrow e^+ \pi^0$  channel: in the plane defined by the invariant mass and the total momentum, crosses represent background and spots signal events. The band indicates the cut region ( $0.86 \text{ GeV} < \text{Total Energy} < 0.95 \text{ GeV}$ ), i.e. all events inside the band are accepted.

# Liquid Argon's Killer App

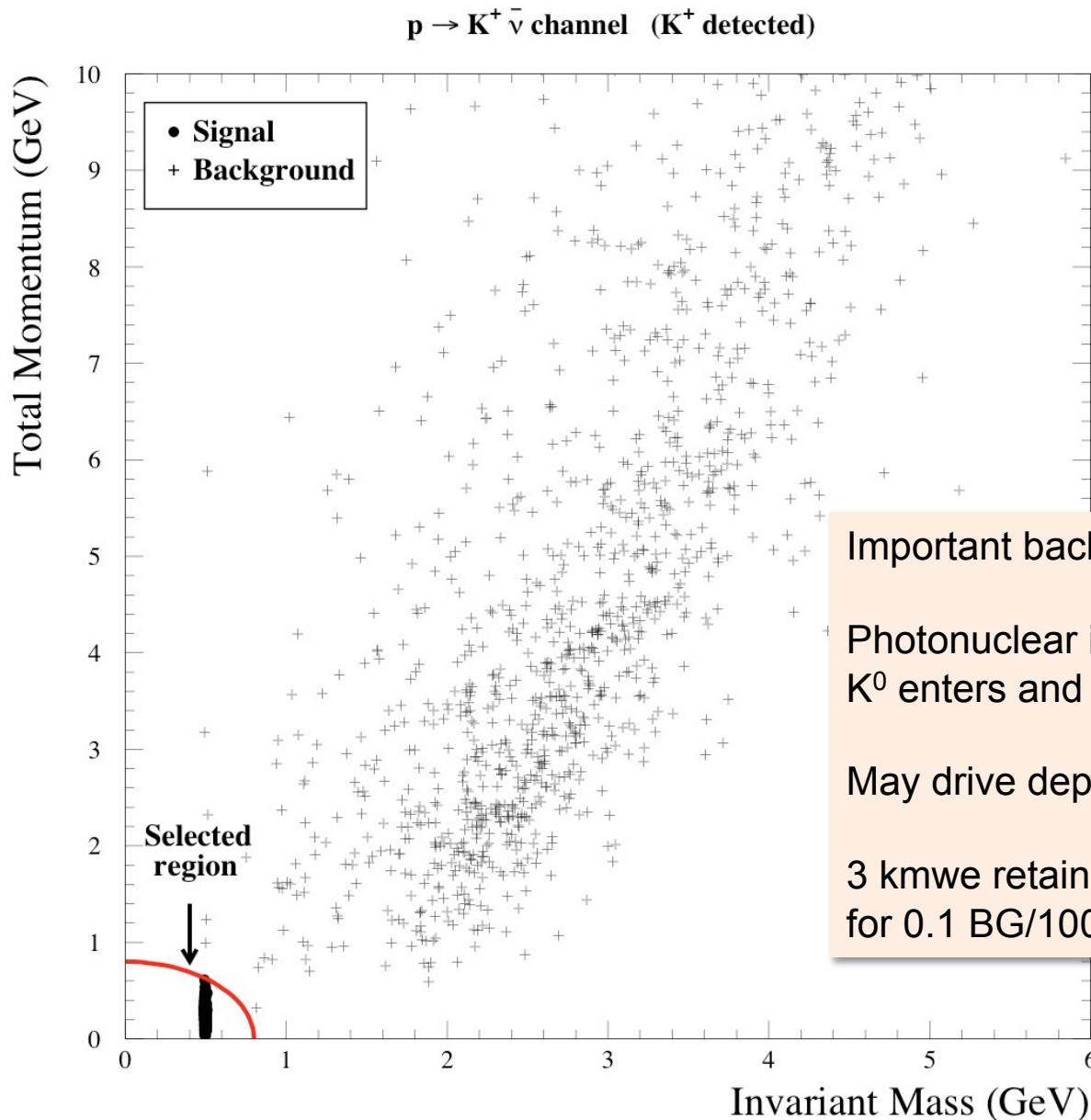


Cuts	(p3) $p \rightarrow K^+ \bar{\nu}$	$\nu_e$ CC	$\bar{\nu}_e$ CC	$\nu_\mu$ CC	$\bar{\nu}_\mu$ CC	$\nu$ NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no $\pi^0$	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

## Warning: A Cheap Photoshop Trick



It would be nice to systematically demonstrate the  $dE/dx$  identification in a neutrino beam, and to quantitatively establish the background rejection.

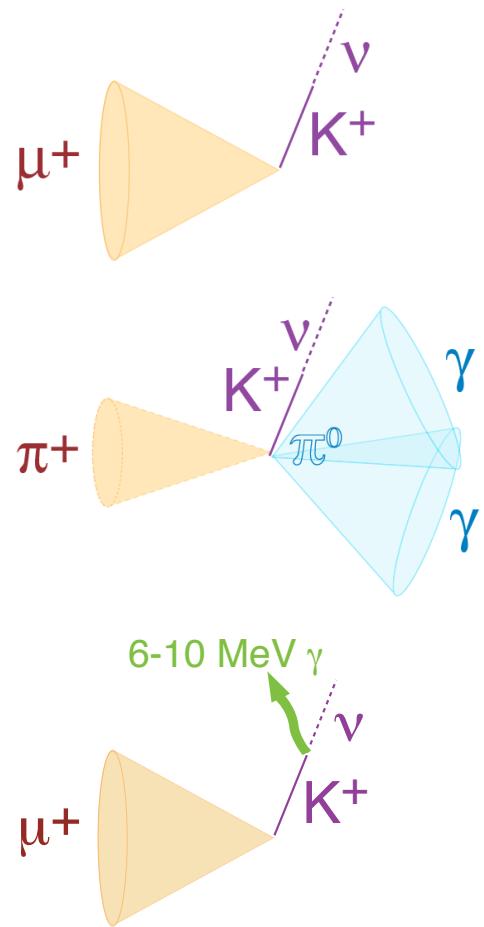


Important background channel:

Photonuclear interaction outside detector  
K<sup>0</sup> enters and charge exchange to K<sup>+</sup>

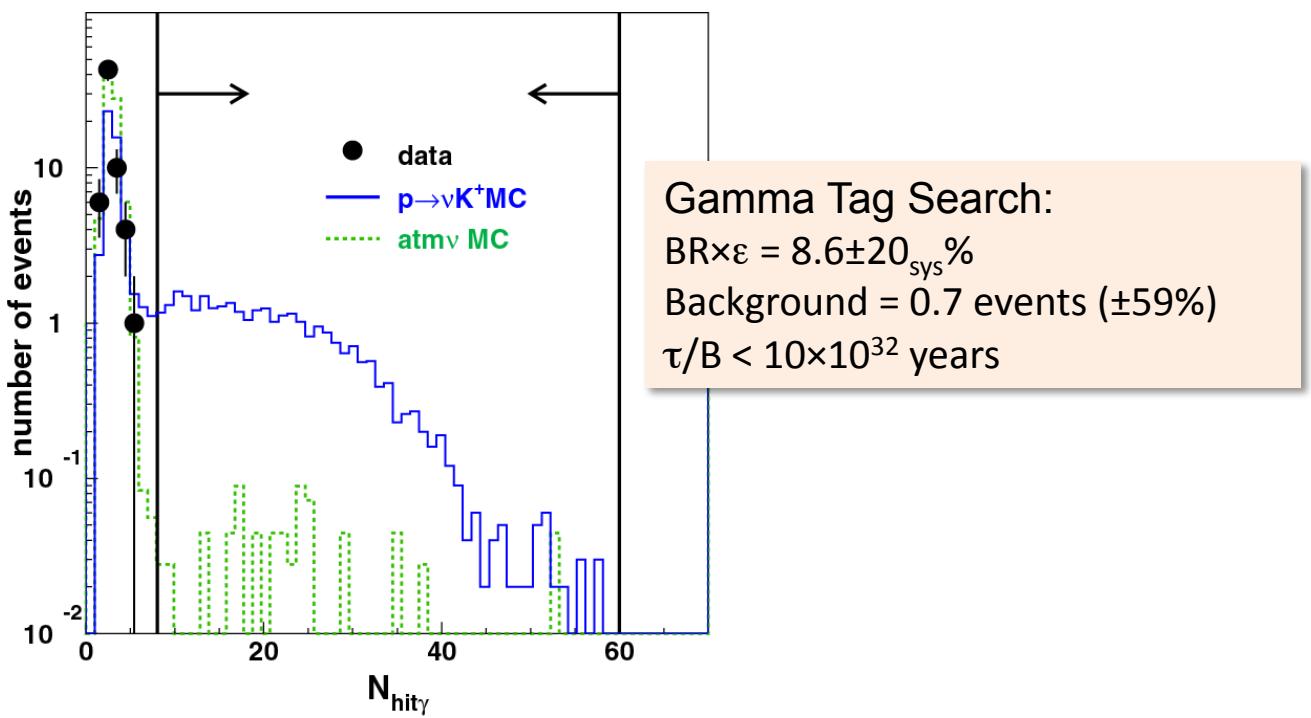
May drive depth / fiducial shielding

3 kmwe retains 90% fiducial mass  
for 0.1 BG/100 kt/yr



## $p \rightarrow K^+ \nu$ in Water Cherenkov

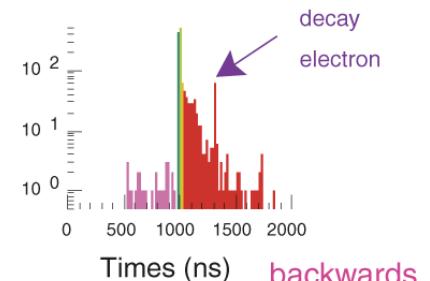
- ★  $K^+$  below Cherenkov threshold
- ★ Essentially a search for  $K^+$  decay at rest
- ★ Three searches (eventually combined)
  - Monochromatic muon (65% BR, large background)
  - $K^+ \rightarrow \pi^+\pi^0$  (21% BR)
  - $K^+ \rightarrow \mu^+ \nu$  with early gamma tag from  $^{16}O^*$



## Super-Kamiokande

Run 1000000 Event 474  
 1997-06-25:12:59:29  
 Time to prev. event: 0.0us  
 Inner: 1395 hits, 2128 pE  
 Outer: 16 hits, 9 pE (in-time)  
 Trigger ID: 0x03

## Forward-backward hemisphere view of Monte Carlo event

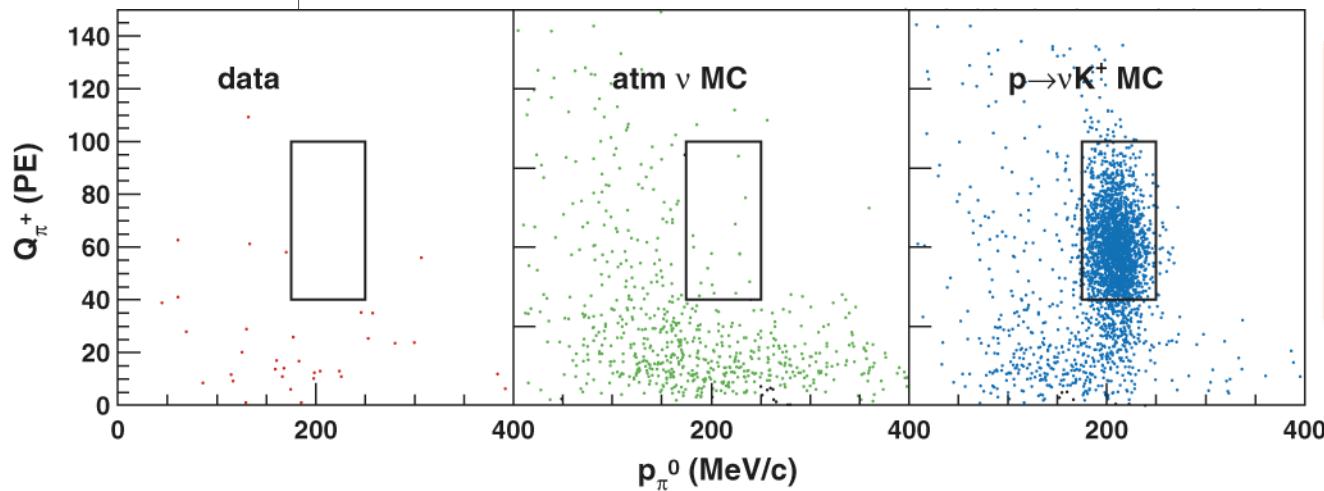
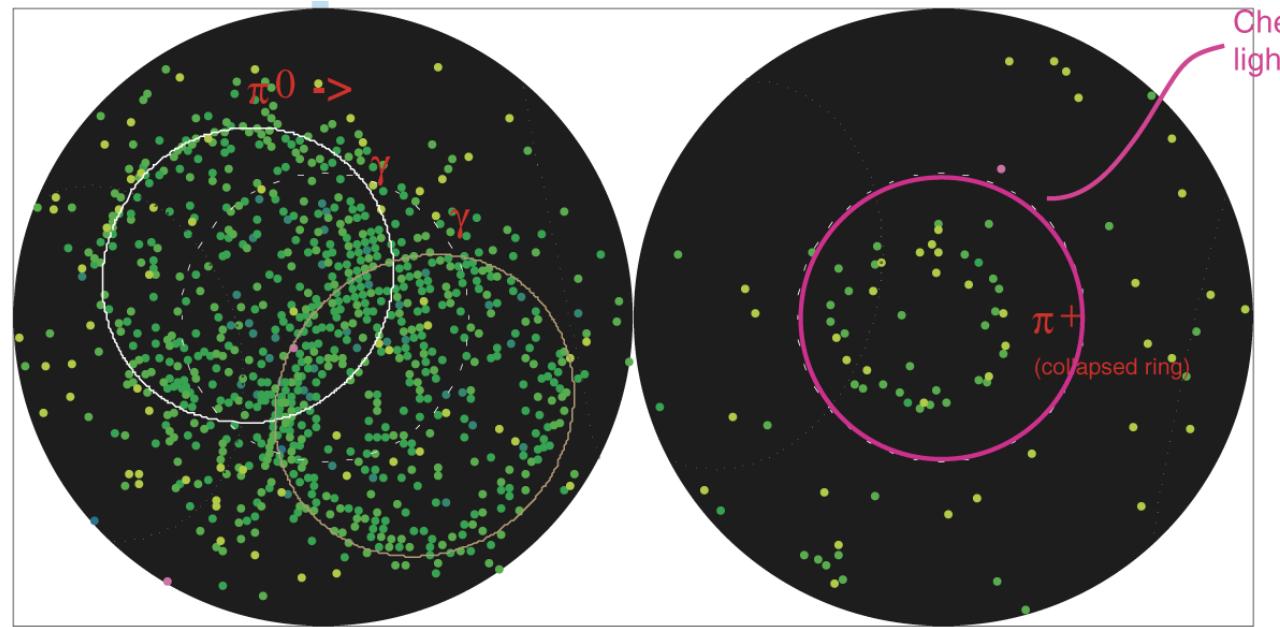


Times (ns)

backwards  
Cherenkov  
light cone

**Resid(ns)**

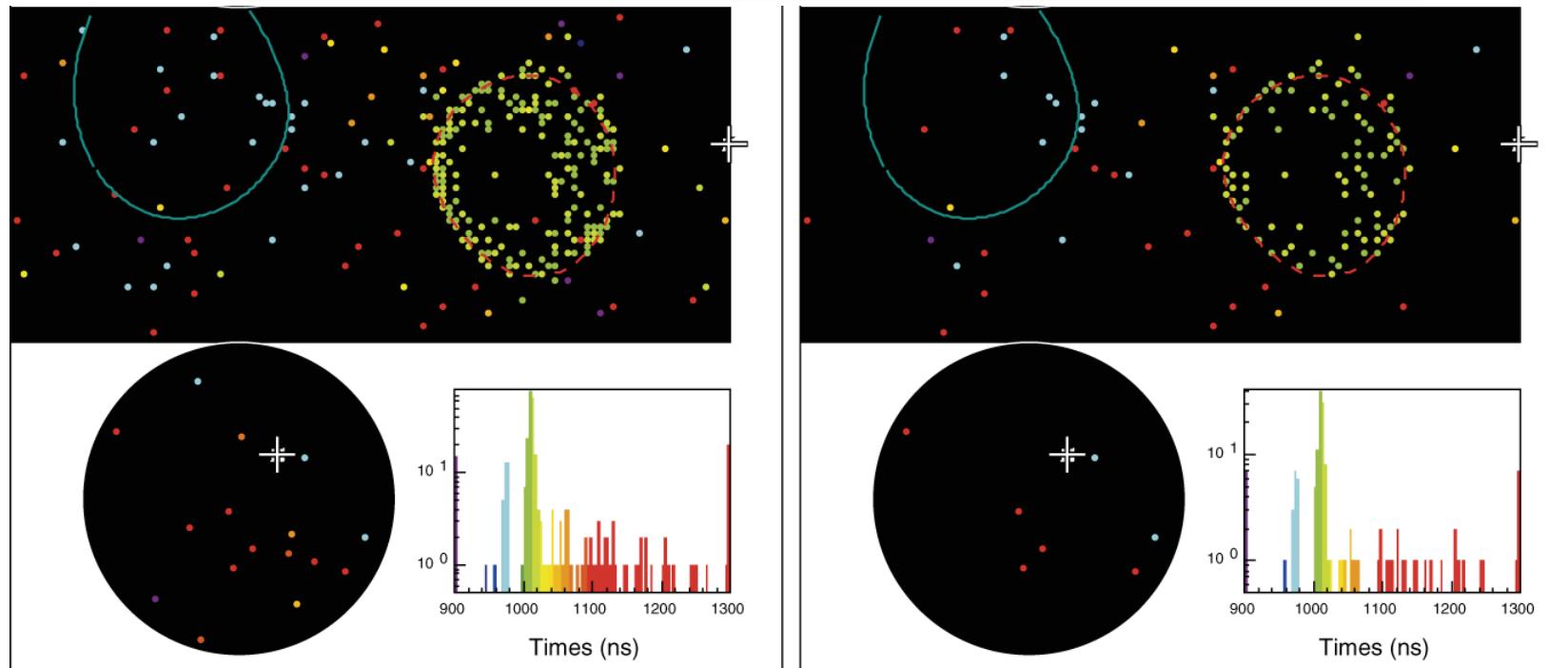
- > 45
- 40- 45
- 34- 40
- 28- 34
- 22- 28
- 17- 22
- 11- 17
- 5- 11
- 0- 5
- -5- 0
- -11- -5
- -17- -11
- -22- -17
- -28- -22
- -34- -28
- < -34



pi<sup>+</sup>pi<sup>0</sup> Search:  
 BR×ε = 6.0±8.8<sub>sys</sub> %  
 BG = 0.6 events (±74%)  
 τ/B < 7.8×10<sup>32</sup> years

Re-optimization for SK-II	SK-I	SK-II
$N_{\text{hit}} \gamma$ (prompt gamma)	7-60 hits	5-30 hits
Backwards light ( $\pi^+\pi^0$ )	40-100 p.e.	20-50 p.e.
Plus a few other cuts such as light outside cone, proton rejection cuts		

SK-II: Efficiency ↓, background ↑, need more work !



# 40% or 20% Photon Coverage?

	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm ( $\mu$ -like)	30 cm (e-like) / 29 cm ( $\mu$ -like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% ( $\mu$ -like)	0.69% (e-like) / 0.96% ( $\mu$ -like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% ( $\mu$ -like)	6.3% (e-like) / 4.0% ( $\mu$ -like)
p $\rightarrow$ e $^+ \pi^0$ signal efficiency	45.0 $\pm$ 1.3 $\pm$ 6.7%	42.2 $\pm$ 1.2 $\pm$ 6.5%
p $\rightarrow$ e $^+ \pi^0$ background	0.4 ( $\pm$ 35%) events/100kty	0.04 ( $\pm$ 35%) events/100kty
p $\rightarrow$ K $^+\nu, \gamma$ tag signal efficiency	8.4 $\pm$ 0.1 $\pm$ 1.7%	4.7 $\pm$ 0.1 $\pm$ 1.0%
p $\rightarrow$ K $^+\nu, \gamma$ tag background	0.72 ( $\pm$ 28%) events/100kty	1.4 ( $\pm$ 30%) events/100kty
p $\rightarrow$ K $^+\nu, \pi^+\pi^0$ signal efficiency	5.5 $\pm$ 0.1 $\pm$ 0.7%	5.7 $\pm$ 0.1 $\pm$ 0.4%
p $\rightarrow$ K $^+\nu, \pi^+\pi^0$ background	0.59( $\pm$ 28%) events/100kty	1.0( $\pm$ 30%) events/100kty
T2K CC $\nu_e$ likelihood effic.	83.7% ( $\pm$ 0.1% stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

Preliminary numbers, for comparison purposes.  
Final published efficiencies and BG may differ.



Background: events/100 kt•yr

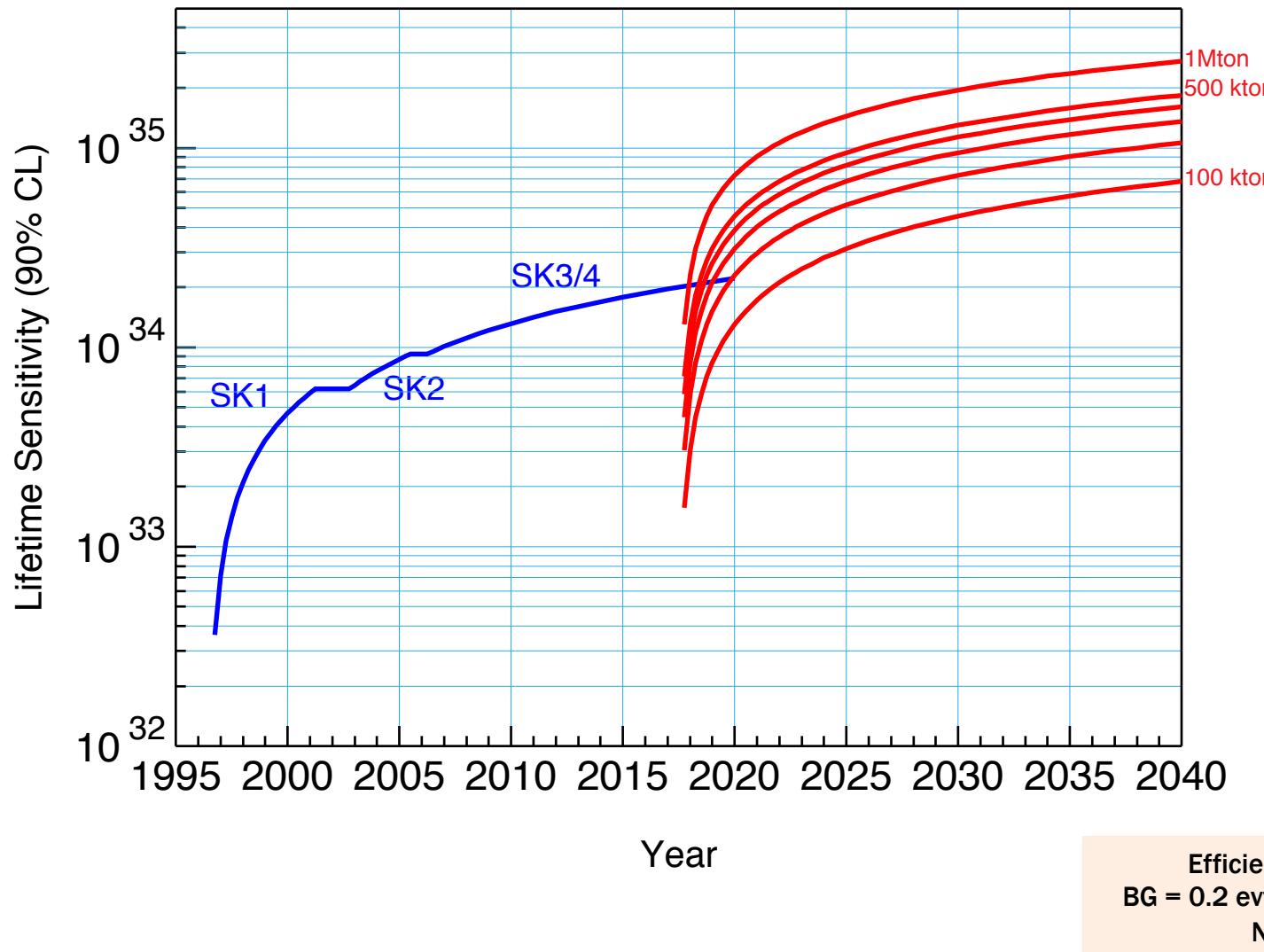
	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^+\pi^0$	45%	0.2	45%	0.1
$p \rightarrow \mu^+\pi^0$	36%	0.2	45%	0.8
$p \rightarrow K^+\nu$	14%	1.3	97%	0.1
$p \rightarrow K^0\mu^+$	8%	0.8	47%	0.2
n-nbar	10%	21		

No advantage for LAr over water for  $e^+\pi^0$ : efficiency dominated by nuclear absorption of the  $\pi^0$  – for both.

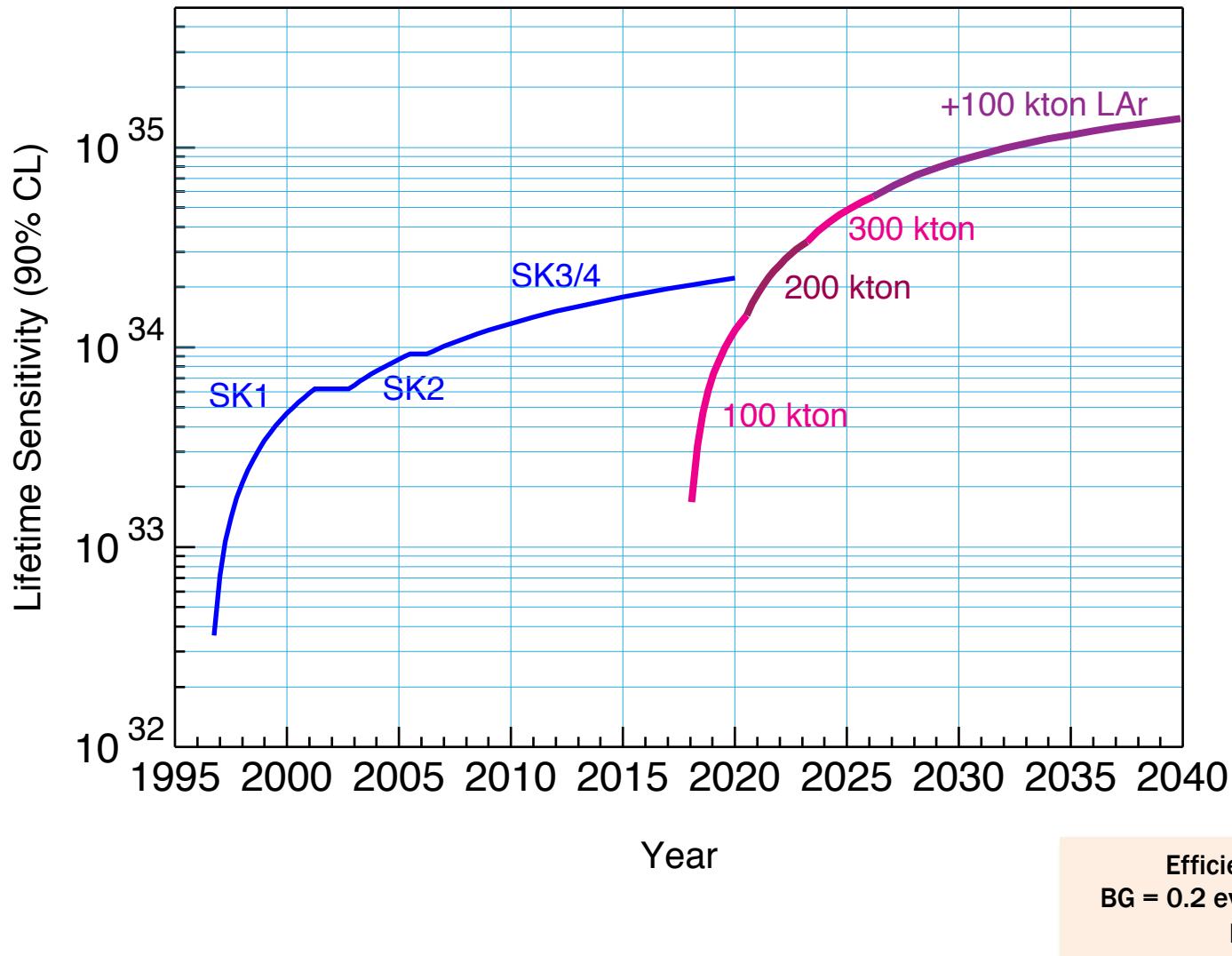
Big advantage for LAr over water for  $K^+\nu$ :  $K^+$  is below Cherenkov threshold but can be identified by  $dE/dx$  in LAr TPC.

LAr should do well with n-nbar: spherical multi-pion final state.

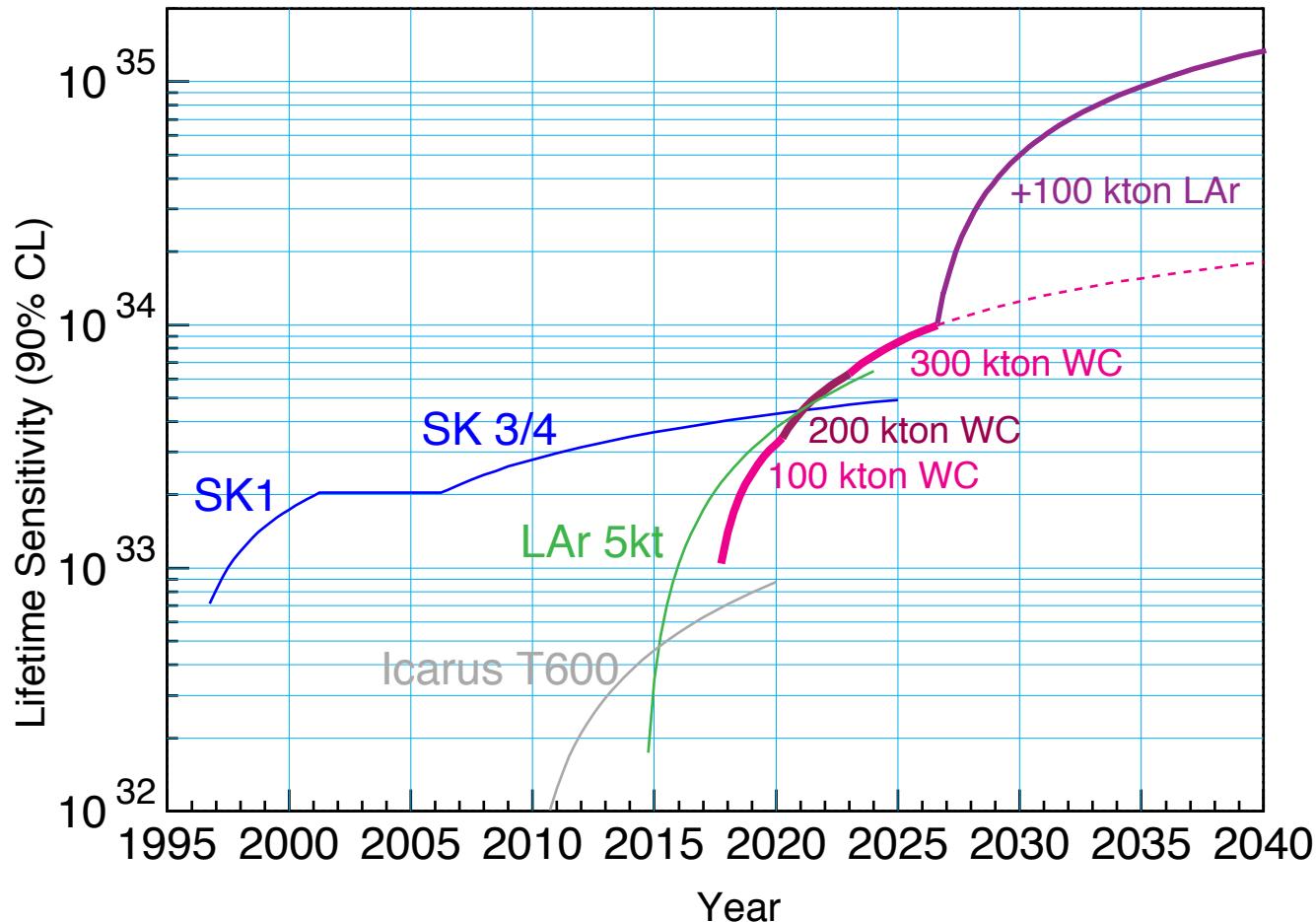
# How big for $p \rightarrow e^+ \pi^0$ ?



$p \rightarrow e^+ \pi^0$



$p \rightarrow K^+ \nu$



WC efficiency = 0.14  
BG = 1.2 evts/100 kty  
Nobs = Nbg

LAr efficiency = 0.98  
BG = 0.1 evts/100 kty  
Nobs = Nbg

# Final opinionated thoughts ...

The non-accelerator physics topics (proton decay & supernova burst especially) provide strong scientific value for a megaton-class detector. It should be designed with multi-decade operation in mind.

These topics require large mass. A fiducial mass of 300 kton (WC) is a minimum for science value. Another 100 kton of LAr could be treated as a 2<sup>nd</sup> generation upgrade, when the technique is further demonstrated. “ $10^{35}$  by 2035” ? Daunting.

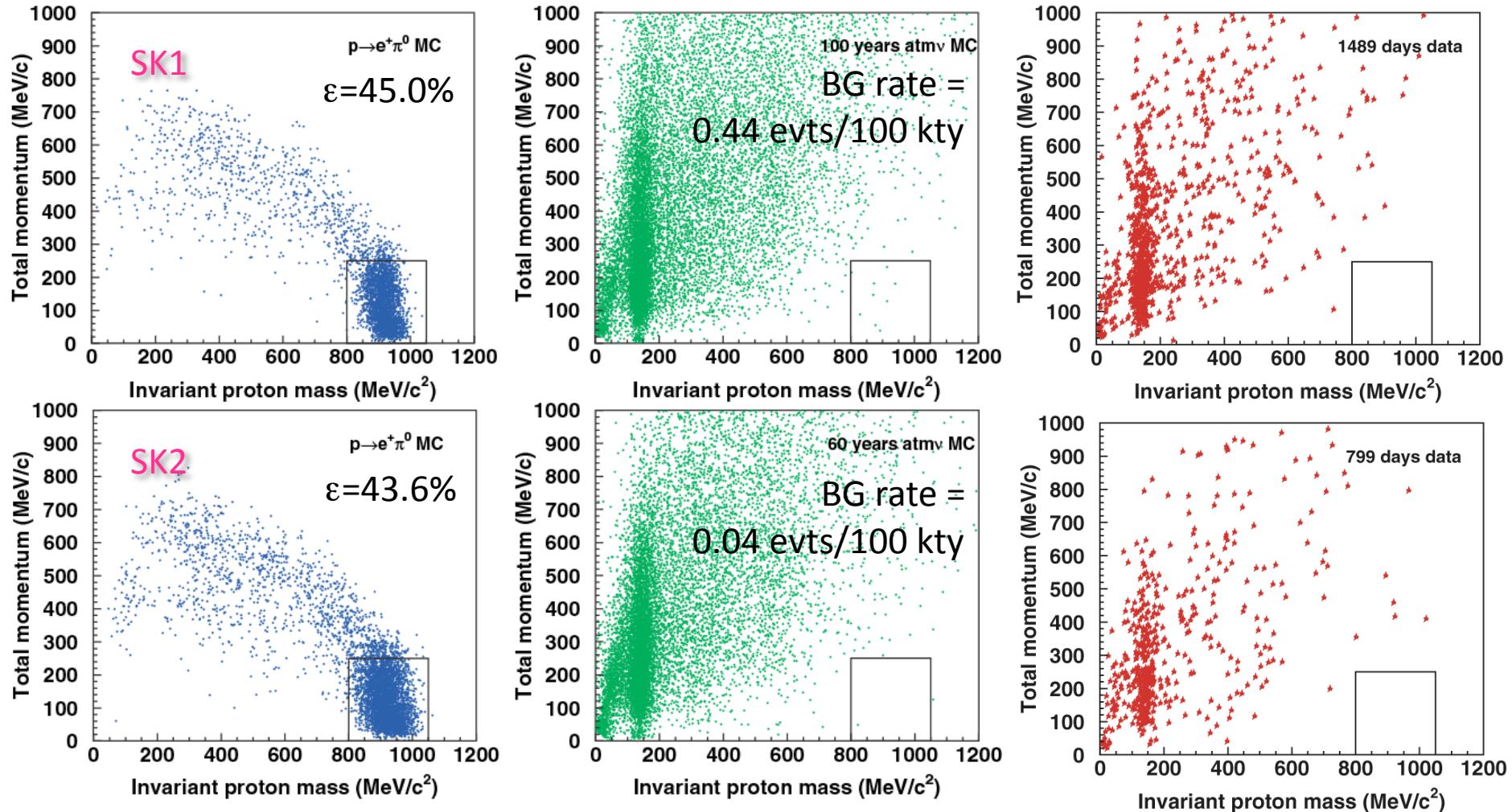
There is merit in both LAr and WC detectors. If SUSY is seen at the LHC, pursuing LAr to 100kt is imperative. If non-SUSY explains EWSB then ???

Even if we see SUSY-style proton decay, we would want to complete the picture of the GUT scale. That will require a whole new approach. Mines and PMTs have run out of steam.

# Backups and Extras



# Super-Kamiokande Results ( $p \rightarrow e^+ \pi^0$ )



Indep. (Nuance MC) BG est. for SK1:

$$\text{BG rate} = 0.21 \text{ evts/100 kty}$$

6 March 2008

BG est. based on K2K 1KT:

$$\text{BG rate} = 0.16 \pm 0.07 \text{ evts/100 kty}$$

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Water Cherenkov - NP08

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# Can we improve?

## ★ Background reduction:

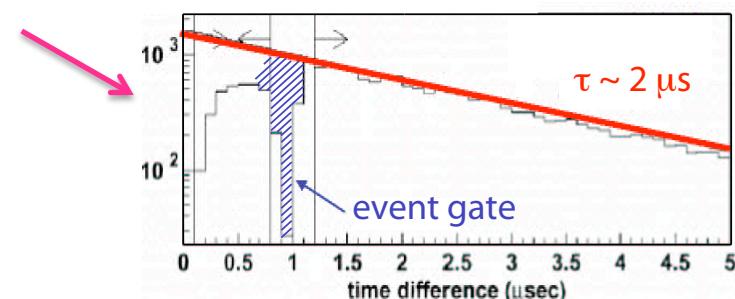
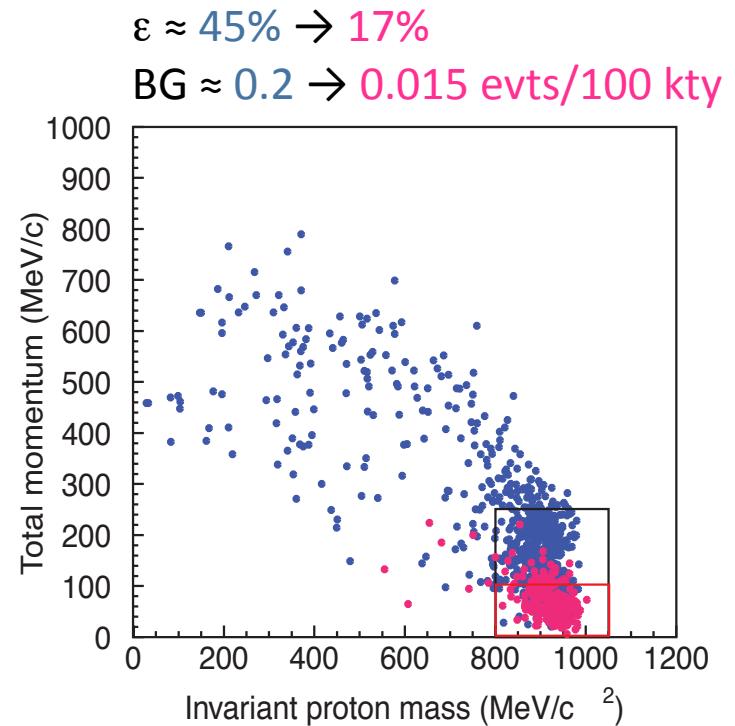
- add 0.2%  $\text{GdNO}_3$
- $n + \text{Gd} \rightarrow 8 \text{ MeV } \gamma, \Delta t = 20 \mu\text{s}$
- many atmospheric  $\nu$  events accompanied by  $n$  (50-90%?)

## ★ Background reduction:

- Tighten cuts for free proton (at expense of efficiency)
- Cross-over in sensitivity:  $\mathcal{O}(10+ \text{ Mton}\cdot\text{yr})$

## ★ Increase efficiency

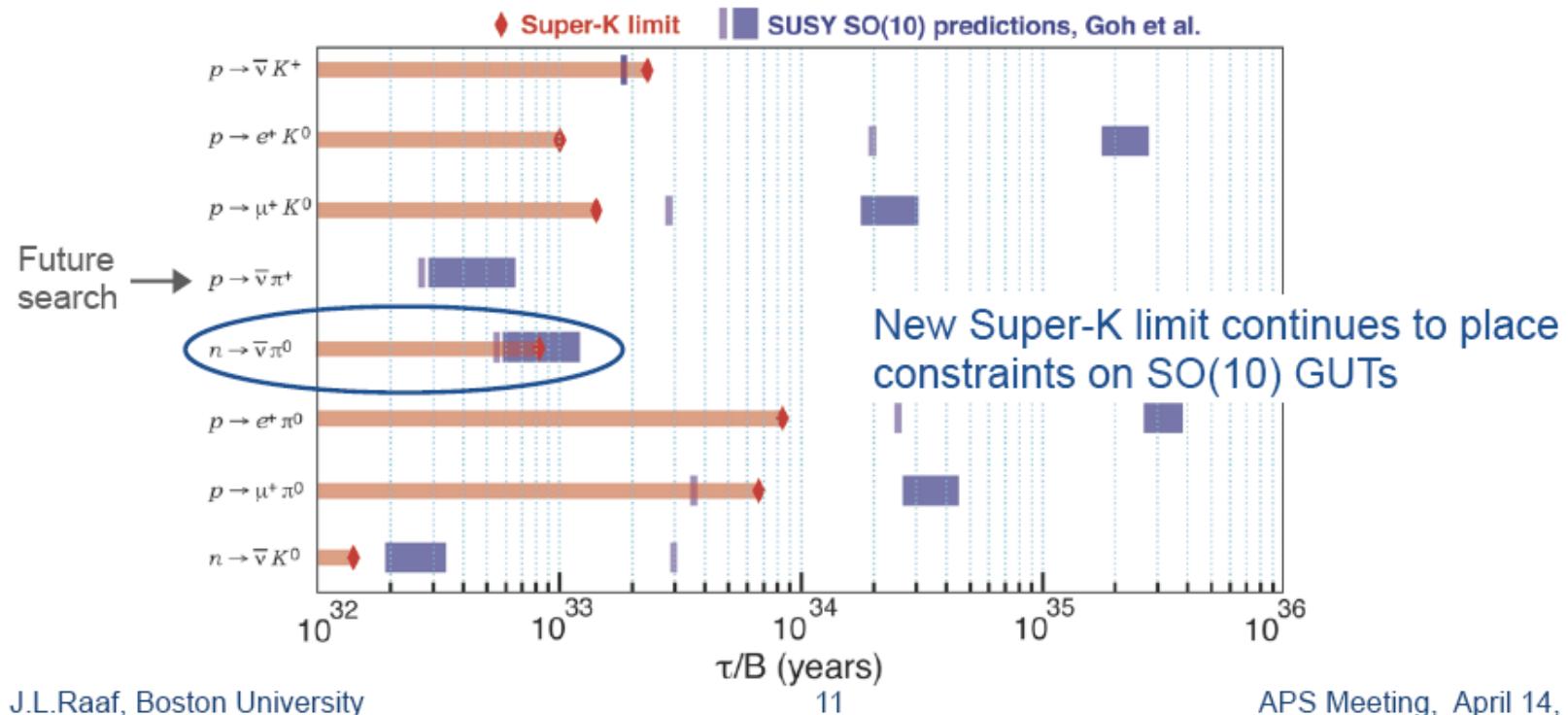
- New SK electronics and DAQ (2008)
- ethernet readout, less deadtime  
→ increased decay electron efficiency
- Generally better performance



Fitting via  $\chi^2$  with systematic pull terms allows Super-K to set a lower limit on the decay mode  $n \rightarrow \bar{v} \pi^0$ :

$$\text{SK-1+2 result: } \tau(n \rightarrow \bar{v} \pi^0) > 8.8 \times 10^{32} \text{ years}$$

Previous best experimental limit by IMB:  $\tau(n \rightarrow \bar{v} \pi^0) > 1.12 \times 10^{32} \text{ years}$



J.L.Raab, Boston University

APS Meeting, April 14, 2008

## Upper Lifetime Limit for $^{16}\text{O}(\text{pp}) \rightarrow ^{14}\text{C} K^+ K^-$

$$\frac{\tau}{B.R.} > \frac{A N_d \epsilon}{S_{90}}$$

$$\frac{\tau}{B.R.} > 6.2 \times 10^{31} \text{ years}$$

A : Exposure = 91.5 kTon yrs for "SK1"

$N_d$  : Number of Oxygen nuclei =  $3.3 \times 10^{31} \text{ } ^{16}\text{O}$  kTon $^{-1}$

$\epsilon$  : Efficiency = (B.R. = 63.43% x 63.43%) x  
(kaon hadronic survival rate = 64.8%) x  
( $K^+ K^- \rightarrow \mu^+ \nu_\mu \mu^+ \nu_\mu$  search efficiency = 18.2%) = 4.7%

$S_{90}$  : Signal limit at 90% CL = 2.3

B: expected number of Background events = 0.2

$N_c$  : Number of candidate events = 0

CL: Confidence Level = .90

Including the systematic uncertainty on efficiency (20.0%) gives...

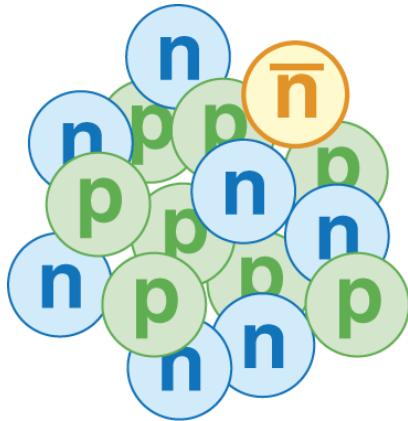
$$\frac{\tau}{B.R.} > 5.7 \times 10^{31} \text{ years}$$

*First measurement of dinucleon decay into kaons ever! Order of magnitude greater than Frejus limits on non-kaon modes.*

This yields a limit on the R-Parity violating coupling constant:

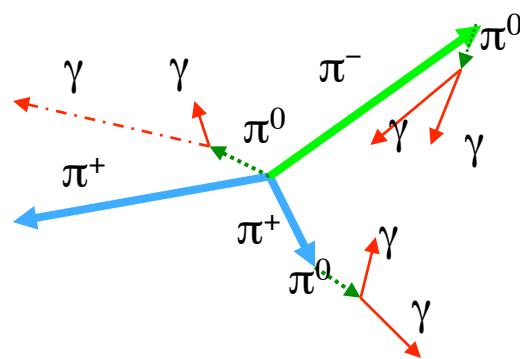
$$\lambda_{uds}'' < 1 \times 10^{-8}$$

*Order of magnitude smaller than theoretical calculation.*



# Neutron – antineutron Oscillation

- ❖ Antineutron annihilates with nearby  $n$  or  $p$
- ❖ Energy release  $\sim 2 \times$  nucleon mass
- ❖ High multiplicity  $\sim 4\pi/\text{event}$
- ❖ Isotropic distribution
- ❖ Final state simulation from bubble chamber data



$\bar{n} + p$

$\pi^+\pi^0$	1%
$\pi^+\pi^0\pi^0$	8%
$\pi^+\pi^0\pi^0\pi^0$	10%
$\pi^+\pi^+\pi^-\pi^0$	22%
$2\pi^+\pi^-2\pi^0$	36%
$2\pi^+\pi^-\omega$	16%
$3\pi^+2\pi^-\pi^0$	7%

$\bar{n} + n$

$\pi^+\pi^-$	2%
$\pi^0\pi^0$	1.52%
$\pi^+\pi^-\pi^0$	6.48%
$\pi^+\pi^-\pi^0\pi^0$	11%
$\pi^+\pi^-\pi^0\pi^0\pi^0$	28%
$2\pi^+\pi^-$	7%
$2\pi^+\pi^-\pi^0$	24%
$\pi^+\pi^-\omega$	10%
$2\pi^+\pi^-\pi^0\pi^0$	10%

# Results:

10.4 % detection efficiency  
 sys. uncertainty 15.2%  
 (mostly intranuclear scattering)

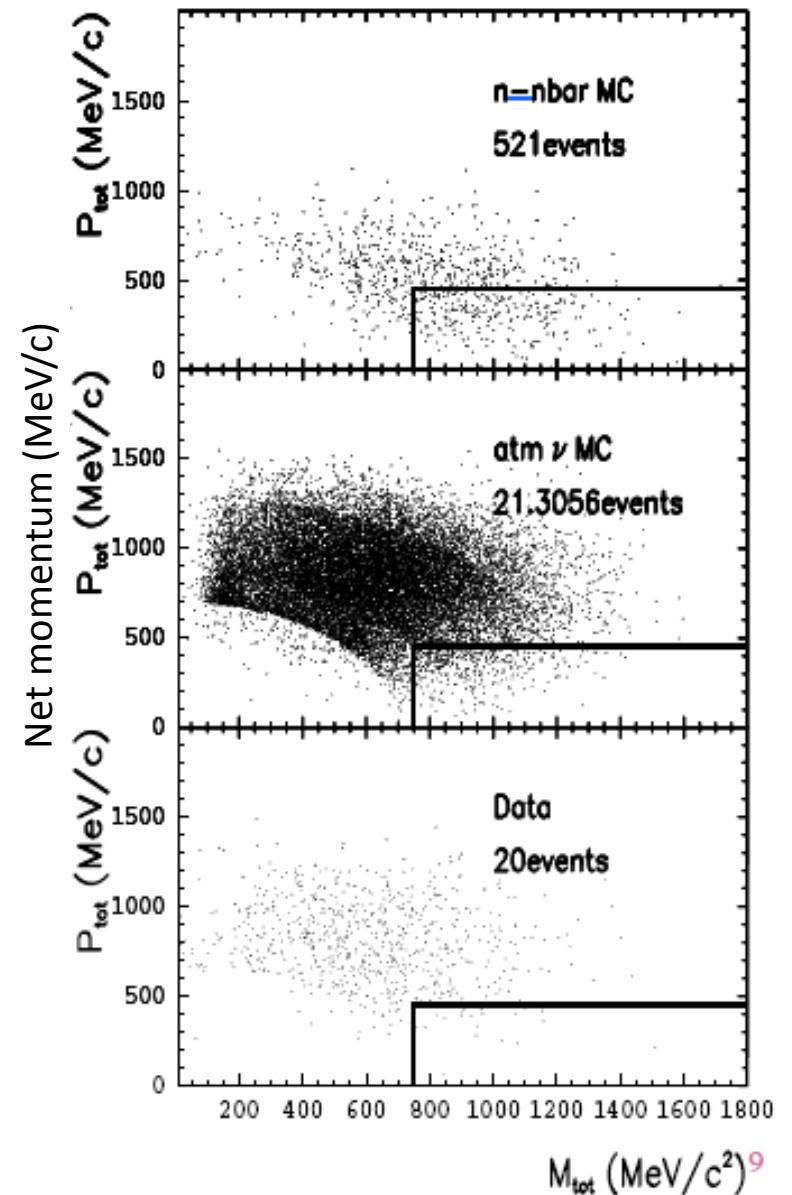
21.3 background events  
 ν osc. effects are included  
 sys. uncertainty 32%  
 (mostly flux, cross sections)

20 candidates

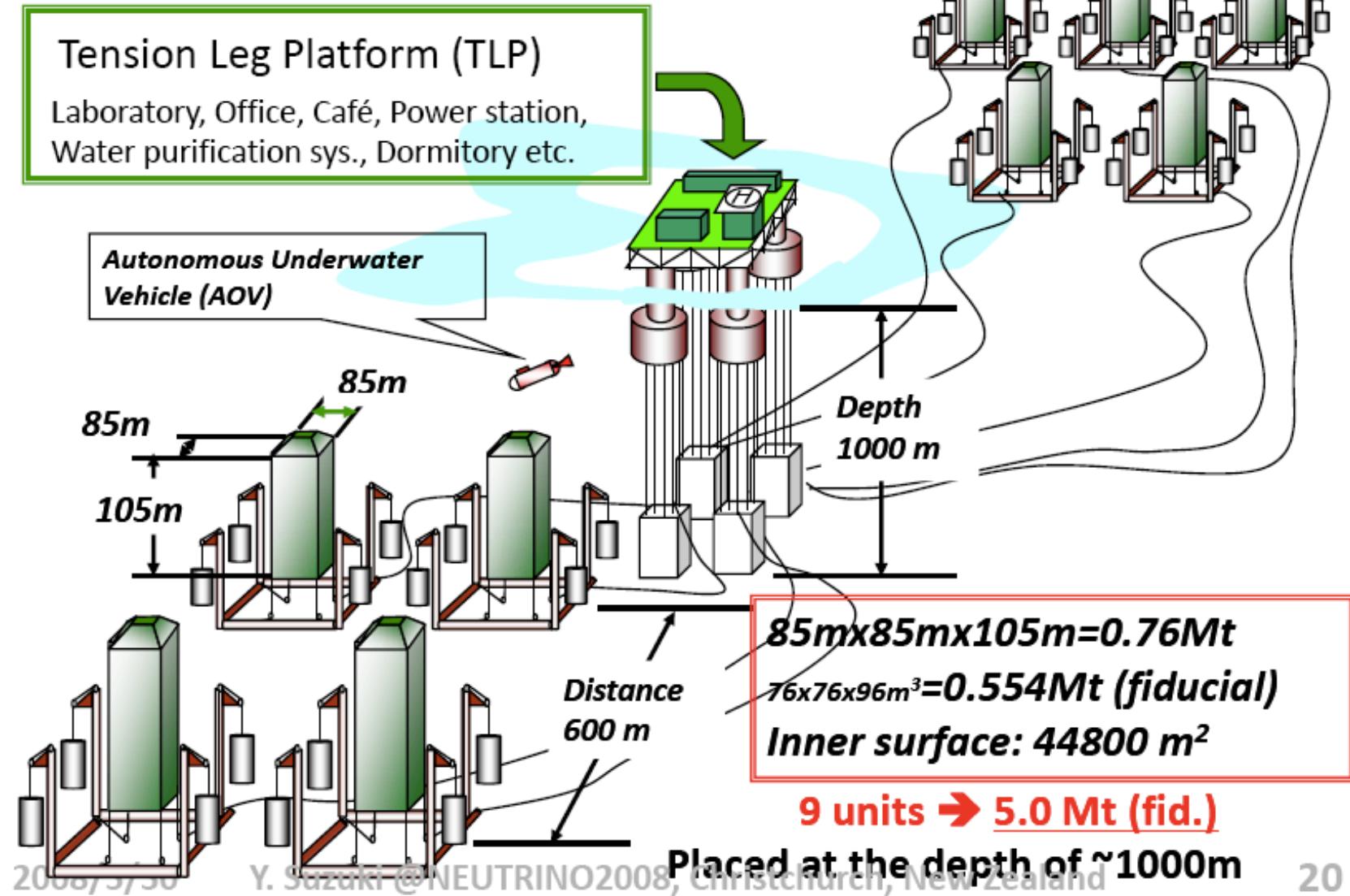
$$\tau_{bound} = \frac{1}{\Gamma_{limit}} = 1.77 \times 10^{32} \text{ yrs (90% CL)}$$

$$\sqrt{\tau} / (R = 1 \times 10^{23} \text{ s}^{-1}) = T_{free} > 2.36 \times 10^8 \text{ s}$$

cf ILL Reactor Expt:  $T_{free} > 0.86 \times 10^8 \text{ s}$



# Deep-TITAND (under water)



20

